Spatially Resolved Flow Velocity-measurements Using Laser-induced Fluorescence From A Pulsed Laser

Westblom, U; Aldén, Marcus

Published in:
Optics Letters

DOI:
10.1364/OL.14.000009

1989

Spatially resolved flow velocity measurements using laser-induced fluorescence from a pulsed laser

Ulf Westblom and Marcus Aldén

The Combustion Centre, Lund Institute of Technology, P.O. Box 118, S-221 00 Lund, Sweden

Received April 29, 1988; accepted October 21, 1988

We describe how spatially resolved velocity measurements can be acquired using a pulse-amplified single-mode cw laser with a potential of single-shot measurements. The laser beam was tuned to the point of maximum slope of a Doppler-broadened absorption profile of I_2, which was seeded into the flow. The beam was then split into two components and sent counterpropagating through the measurement region. By diode-array detection of the laser-induced fluorescence from I_2, spatially and temporally resolved velocities can be acquired.

Many laser spectroscopic techniques have recently become some of the most important tools in the understanding of different combustion and flow phenomena. One of these is laser-induced fluorescence (LIF), which has been used mostly for temperature determination and concentration measurements of minor species (see, e.g., Refs. 1 and 2). One important advantage of LIF is the possibility of making multiple-point measurements through imaging experiments using one- or two-dimensional detectors. This technique was first demonstrated in one dimension using a diode-array detector,[3] followed by two-dimensional measurements[4,5] and multiple-species (C_2, OH) detection.[6] Recently even three-dimensional images have been presented.[7]

In addition to temperature and concentration determinations, velocity measurements are of vital importance for a deeper understanding of various combustion and flow phenomena. It has been shown how spatially resolved velocity measurements can be achieved by using a single-mode cw laser tuned to a Doppler-broadened absorption line profile.[8–10] In these experiments the time resolution has been in the millisecond regime owing to limitations in the signal strength. However, in order to freeze turbulent velocity fluctuations over the full frequency range of interest, a technique with submicrosecond resolution is required. This will permit accurate sampling of the full range of velocity fluctuations in turbulent flows and hence give access to averages of second and higher moments of the velocity. It is also particularly of interest for studies of the correlation between velocity and concentration, which are vital to a deeper understanding of the processes governing reacting turbulent flows. The available techniques do not seem to have the potential for this increase in time resolution by simply going to shorter exposure times while keeping other parameters constant. Other techniques that have been proposed for spatially resolved velocity measurements are, e.g., photothermal deflection[11] and tagging techniques.[12]

In this Letter we report on spatially resolved velocity measurements using a pulse- (10-nsec) amplified cw dye laser, tuned to the point of maximum slope of a Doppler-broadened absorption profile of I_2, that was seeded into the flow, yielding a concentration of approximately 300 parts in 10^6. In the present experiment it was not possible to identify the exact rotational excitation transition, and, since it was not clear how differences in hyperfine structure splittings and spectral perturbations would influence the measurements, several different transitions were examined and found to give consistent results.

The experimental setup is shown in Fig. 1. An argon-ion laser (Spectra-Physics 171-17) pumps a ring dye laser (Coherent 699-21), yielding an output power of ~500 mW with a bandwidth of ~1 MHz at $\lambda = 580$ nm. Part of the beam was split off to monitor the frequency stability with a scanning Fabry–Perot inter-

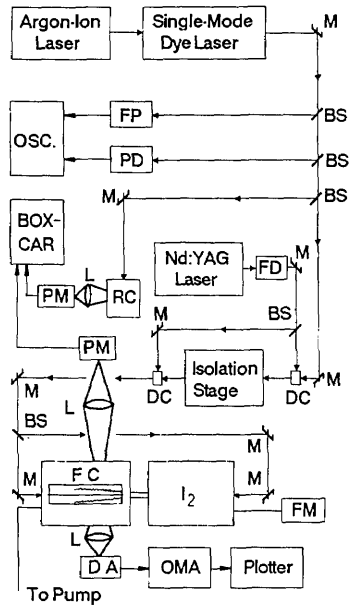

Fig. 1. Experimental setup. M's, Mirrors; FD, frequency doubler; BS's, beam splitters; FC, flow chamber; FM, flow meter; PM's, photomultiplier tubes; DA, diode array; L's lenses.

0146-9592/89/010009-03$2.00/0

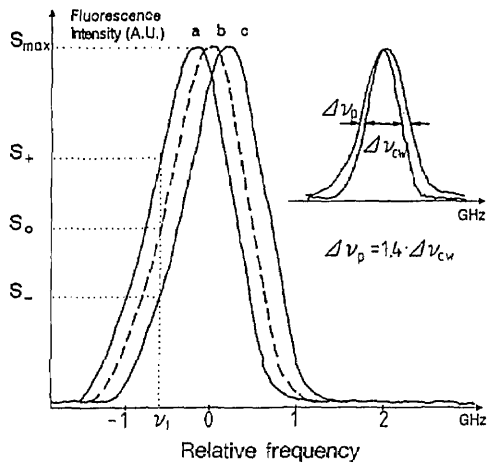

Fig. 2. Experimentally recorded I_2 absorption profiles in the beam direction against the flow (curve a), static gas (curve b), and the beam direction with the flow (curve c). Also shown are line profiles recorded with cw and pulsed lasers (inset).

ferometer, the power with a photodiode (PD), and the I_2 fluorescence intensity from a reference cell (RC). The main part of the cw beam was directed through two amplifying dye cells (DC's), with Kiton Red as the dye, which were pumped by a frequency-doubled Nd:YAG laser (Quantel YG 581-10). The pump energies were 2 mJ for the first stage and 25 mJ for the second, yielding output energies of 5 μJ and 3 mJ, respectively, with a frequency width of ~150 MHz. A dispersive isolation stage between the dye cells gave a reduction in the amplified spontaneous emission of less than 1% in the final pulse. The pulse-amplified beam was then divided into two beams that were focused by $f = 700$ mm lenses and sequentially directed, counterpropagating, through the flow chamber. The flow facility, which was built to simulate a free expanding jet, consisted of two chambers in sequence. This arrangement was made in order to avoid shock phenomena, and thereby large pressure gradients, in the test section. The chambers were evacuated to pressures of 10 and 70 Torr, respectively. A Nikon $f/1.4$ lens was used to image the fluorescence directly onto an intensified diode-array detector (PARC OMA III) with 1024 pixels through a cutoff filter (Schott OG 590).

In Fig. 2, experimentally recorded LIF excitation profiles are shown of I_2 in a cell with the beam direction against the flow (curve a), no flow (curve b), and the beam direction with the gas flow in the flow chamber (curve c). The shift, $\delta\nu$, between the profiles obtained in the flow and in the static cell is due to the Doppler effect and is related to the flow velocity by $\delta\nu = v/\lambda$, where λ is the laser wavelength and v is the velocity. If the slope of the profile, to a first approximation, is considered to be constant around the point of maximum derivative, where the laser frequency is positioned, the following expression can be derived[9]:

$$v = \frac{S_+ - S_-}{S_+ + S_-} \lambda \frac{g(\nu_1)}{g'(\nu_1)}, \qquad (1)$$

where S_+ and S_- are the fluorescence intensities from the different beams, λ is the laser wavelength, $g(\nu_1)$ is the value of the normalized absorption profile at the laser wavelength, and $g'(\nu_1)$ is the value of the function derivate at this point. The advantage of this expression is that the velocity v is expressed in factors that are independent of laser power, quenching, and seeding concentration. As can be seen from Fig. 2, the absorption profiles recorded with the pulsed amplified laser are broader than the profile using the pure cw laser, 1.5 and 1.1 GHz, respectively. The broadening of the absorption profile is due to saturation broadening and the use of a laser with a larger bandwidth for excitation. In addition, there are contributions to the line shape from amplified spontaneous emission and from sidebands in the pulse-amplified laser owing to mode beating, since the Nd:YAG laser was multimode (~1 cm^{-1}).[13] These phenomena and possibly spurious scattered light were taken into account when calculating the flow velocity.

Measurements were made using the system in both the cw and pulsed modes. A comparison between velocity recordings obtained with the cw and pulsed techniques is shown in Fig. 3. As can be seen, the velocity distributions acquired with the pulsed technique are similar to the recordings taken in the cw mode, when the difference in absorption line profile is taken into account. In Fig. 4, single-shot recordings are also shown for the beam direction against the flow (curve a), no flow (curve b), and the beam direction with the flow (curve c). The three recordings were made at the same pressure, 10 Torr, and yielded within a factor of 4 the same number of counts on the diode array. The difference in rms values between the recordings with flow and without flow is attributed to time-resolved turbulence. Since only one diode-array detector was available for the time of the experiment, the recordings for the left and the right beam were made with a time difference of 100 msec; consequently, the velocities from these recordings would not give the true time-resolved values. To do this two detectors would have to be used, gated sequentially since the readout time of most detector systems is considerably longer than the turbulent time scale. Thus, by gating the detector on each of the two counterpropagating beams, a time resolution of less than 100 nsec will be achieved. This can of course also be achieved

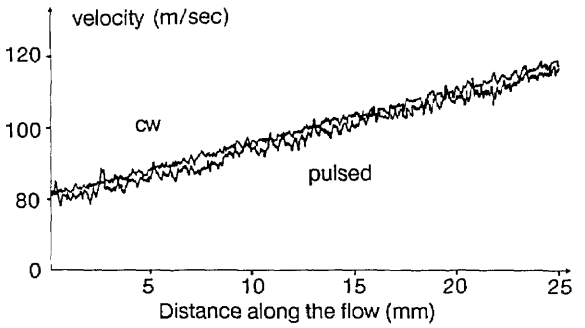

Fig. 3. Comparison between velocity recordings using pulsed- and cw-laser techniques.

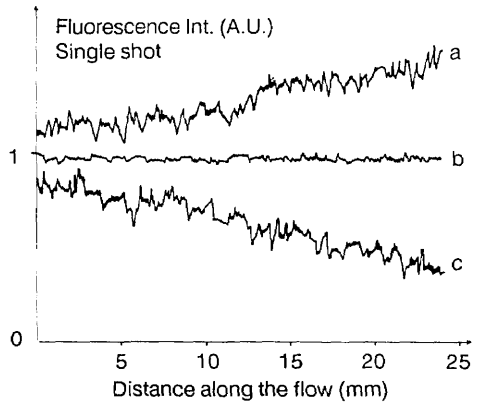

Fig. 4. Normalized single-shot recordings with the beam direction against (curve a) and the beam direction with (curve c) the flow. Curve b is taken in static gas at the same pressure.

in two dimensions by using diode matrixes as detectors, as has been done with cw lasers.[8,10]

In evaluating the velocities it is necessary to monitor the spectroscopic factor, $g(\nu_1)/g'(\nu_1)$, in Eq. (1) since it changes with pressure and temperature. Thus it is important that the values of these parameters are constant through the probe volume or that they can be measured *in situ*.

The flow studied in this experiment was designed to have small temperature and pressure gradients to circumvent this problem. The low pressures used reflect the problem with collisional deexcitation—quenching—in LIF. When the pressure is raised the collision rate will increase, and hence the quenching increases, which reduces the fluorescence intensity. At the same time, the number density will also increase, but only until the vapor pressure of the species is reached, which for I_2 is below 1 Torr. Thus raising the pressure above this value only increases the quenching but not the number density. Under the experimental conditions reported here an increase in pressure from 10 to 200 Torr caused a decrease in signal intensity by a factor of 10. It can be shown that the dependence of pressure is reduced if the laser power becomes large, i.e., the transition becomes saturated. Operation in the saturated regime thus has the advantage of decreasing the pressure dependence of the fluorescence signal. Another advantage to working in the saturated mode is that it also reduces the sensitivity to changes in laser power due to, e.g., absorption. However, since the saturation effect makes the shape of the absorption profile dependent on laser power, focusing, and laser bandwidth, it is important that the velocity measurements are recorded under the same conditions as those when the shape of the absorption profile is measured.

In the experiments reported here, I_2 was chosen as the test species because of its high vapor pressure and easily accessible spectra in the visible region. However, it is clear that this species is not an optimal seeding species, since it is poisonous and corrosive and, compared with species naturally occurring as a gas, its concentration is low. The useful measurement range in I_2 is also limited to below approximately 200 Torr since transitions start to overlap above this pressure owing to pressure broadening. For the technique to have general usefulness in studying turbulent fluctuations, these limitations with I_2 have to be overcome.

Consequently, an alternative to I_2 would be advantageous. Unfortunately, most stable species have their absorption bands in the UV or VUV spectral regions. However, these wavelengths can be reached by nonlinear processes such as frequency mixing and doubling and/or by using multiphoton processes. Both of these alternatives are possible in the pulsed-laser approach but hardly in the cw-laser approach.

The optimum choice as a seeder in many respects would be N_2. Unfortunately, its resonances lie well down in the VUV. However, recently N_2 was detected in the atmosphere using a multiphoton process near 280 nm with UV and near-UV fluorescence,[14] which will also be considered for velocity measurements in the future using the technique proposed here.

The authors gratefully acknowledge the constant support and help from S. Svanberg. We also thank S. Kröll, B. Norén, and G. Holmstedt for stimulating discussions and help during the course of this work and P. Hutchinson, Cranfield Institute of Technology, for helpful suggestions on the manuscript. This research was financially supported by the National Swedish Energy Board and the National Swedish Board for Technical Development.

References

1. K. Schofield and H. Steinberg, Opt. Eng. **20,** 501 (1984).
2. D. R. Crosley, J. Chem. Educ. **59,** 446 (1982).
3. M. Aldén, H. Edner, G. Holmstedt, S. Svanberg, and T. Högberg, Appl. Opt. **21,** 1236 (1982).
4. M. J. Dyer and D. R. Crosley, Opt. Lett. **7,** 382 (1982).
5. G. Kychakoff, R. D. Howe, R. K. Hanson, and J. C. McDaniel, Appl. Opt. **21,** 3225 (1982).
6. M. Aldén, H. Edner, and S. Svanberg, Appl. Phys. **B29,** 93 (1982).
7. R. K. Hanson, in *Proceedings of the Twenty-First International Symposium on Combustion* (The Combustion Institute, Pittsburgh, Pa., 1986), p. 1677.
8. J. C. McDaniel, B. Hiller, and R. K. Hanson, Opt. Lett. **8,** 51 (1983).
9. U. Westblom and S. Svanberg, Phys. Scr. **31,** 402 (1985).
10. B. Hiller and R. K. Hanson, Appl. Opt. **27,** 33 (1988).
11. J. A. Sell and R. J. Cattolica, Appl. Opt. **25,** 1420 (1988).
12. R. Miles, C. Cohen, J. Connors, P. Howard, S. Huang, E. Markovitz, and G. Russell, Opt. Lett. **12,** 861 (1987).
13. L. Rahn, Sandia National Laboratory, Livermore, California 94550 (personal communication).
14. M. Aldén and W. Wendt, "Detection of nitrogen molecules through multiphoton laser excitation and N_2^+ fluorescence," Opt. Commun. (to be published).