Imaging Measurements of Flow Velocities using Laser-Induced Fluorescence

This article has been downloaded from IOPscience. Please scroll down to see the full text article.
1985 Phys. Scr. 31 402
(http://iopscience.iop.org/1402-4896/31/5/014)

View the table of contents for this issue, or go to the journal homepage for more

Download details:
IP Address: 130.235.188.41
The article was downloaded on 14/07/2011 at 09:09

Please note that terms and conditions apply.
Imaging Measurements of Flow Velocities using Laser-Induced Fluorescence

U. Westblom and S. Svanberg

Department of Physics, Lund Institute of Technology, P.O. Box 118, S-221 00 Lund, Sweden

Received January 8, 1985; accepted February 21, 1985

Abstract

Imaging velocity measurements along a line through a flowing gas are described. Laser-induced fluorescence from I$_2$ molecules, used to seed the flow, was utilized. A method of alternating counter-propagating beams from a single-mode dye laser, acting in the wing of the Doppler-shifted molecular absorption profile was used. Some improvements to the technique are also suggested.

1. Introduction

Measurements of flow velocities are important in fields such as fluid mechanics, combustion and aeronautics. Many methods, such as hot-wire techniques and particle-streak photography, have been developed. Optical techniques are desirable since they provide non-intrusive measurements and the potential of simultaneous multi-point measurements. However, the most commonly used optical technique, Laser Doppler Anemometry (LDA) [1], is a single-point monitoring method which also requires the seeding of the flow with particles. Such particles do not necessarily follow the flow exactly in high-acceleration cases. Laser-Induced Fluorescence (LIF) enables powerful non-intrusive measurements to be made of species concentrations and temperatures in the reactive flows found in combustion.

Fluorescence can be induced along a laser beam and the light can be focused onto an array detector that observes the beam laterally, thus providing spatially resolved information. The first imaging measurements of species concentrations using this technique were reported for OH [2], while measurements of temperature were described for an In seeded flame [3]. Such one-dimensional (1-D) measurements have been extended to C$_2$ using single-photon excitation and to O and CO using two-photon excitation. (For a review see [4]). Two-dimensional (2-D) imaging has also been developed using a sheet of exciting laser light in conjunction with a vidicon or diode-matrix detector [5, 6]. Imaging measurements of hypersonic flows using LIF in Na atoms [7] and I$_2$ molecules [8] have been reported. Here a single-mode CW laser was tuned into the wing of a Doppler-broadened absorption line and the intensity changes when the particles are tuned up and down the line profile corresponding to changing velocities, were recorded photographically [7] or with a diode matrix camera [8]. Much more well-defined measurements can be made by using alternating counter-propagating laser beams. In this case non-uniformities in the seeding and in the illumination can be neglected, and the technique can also be applied to subsonic flows. Such a scheme was recently put forward and illustrated in 2-D measurements by Hiller et al. [9]. This scheme was also conceived in our laboratory and in this paper the results of such measurements are presented. Further, improvements of the technique are proposed, which should considerably extend and facilitate its applications.

2. Theoretical considerations

A brief description of the theoretical background for the present measurements will be made with reference to Fig. 1. The laser is tuned to a frequency in the wing of the absorption line, where a steep slope and a reasonable linearity for small frequency changes can be found. An experimentally determined I$_2$ absorption line is shown in the right part of the figure. The absorption profile is described by a line-shape function $g(v)$, which has the value of unity at the point of maximum absorption. If a fluorescence intensity of I$_m$ is recorded at this frequency ($v_m$) the fluorescence intensity $I_n(v)$ at frequency $v$ for non-flowing gas is given by

$$I_n(v) = I_m g(v)$$  \hspace{1cm} (1)

If the absorption species is moving at a velocity $v$ along the line of interaction, the whole line profile is shifted by $\Delta v$ because of the Doppler effect. For small velocities we have

$$v = c \frac{\Delta v}{v}$$  \hspace{1cm} (2)

and to first order the intensity $I_f(v)$ for flowing gas is

$$I_f(v) = I_m g(v + \Delta v)$$  \hspace{1cm} (3)

The frequency shift $\Delta v$ is detected as an intensity change $\Delta I$ in the wing of the line profile

$$\Delta I = I_f(v) - I_n(v) = I_m \frac{dg(v)}{dv} \Delta v$$  \hspace{1cm} (4)

By using the measured intensities $I_f$ and $I_n$ for laser beams propagating from the left and the right, respectively, $\Delta I$ can be expressed as $(I_f - I_n)/2$, and

$$\Delta I = I_{mf} g(v) = (I_f + I_n)/2 g(v).$$

By combining these expressions with eqs. (2) and (4) we obtain

$$v = \frac{\Delta I}{I_f - I_n} \frac{g(v)}{\frac{dg(v)}{dv}} \frac{c}{v}$$  \hspace{1cm} (5)

This is a useful expression, which is independent of the concentration of the fluorescent species. The expression is derived under the assumption of identical intensities and diameters of the two counter-propagating beams. If this is not the case a correction factor must be applied to one of the intensities.

The spectroscopic factor $g(v)/(dg(v)/dv)$, which is temperature and pressure dependent, must be accurately known in order to allow accurate velocity determinations. I$_2$ rovibronic lines have a complicated line shape since each line consists of either 15 or 21 unresolved hyperfine components. These components can be resolved by using saturation or polarization spectroscopy. I$_2$ lines that overlap with Ar$^*$ lines have been studied by Hansch, Levenson and Schawlow [10]. More arbitrary lines can be chosen with a single-mode dye laser. (See, e.g., [11]). With experimentally known component separations and pressure
broadening coefficients lineshapes can be calculated at a given pressure and temperature. Clearly, the value of \( g(\nu)/dg(\nu)/d\nu \) at the chosen laser frequency can also be measured.

3. Experimental arrangement

The experimental arrangement that was used in the present measurements is schematically illustrated in Fig. 2. A single-mode, actively stabilized dye laser (CR–599) with a linewidth of about 1 MHz was used for inducing fluorescence in I2 molecules that were used to seed the flow. The laser, which was operating with Rhodamine 6G dye in the orange wavelength region, was pumped by an Ar laser (S.–Ph. 171–17). Part of the laser beam was deflected for diagnostic purposes. The single-mode operation was controlled with a scanning Fabry–Pérot interferometer, which in its non-scanning mode was also used for generating frequency marks for frequency sweep calibration. A digital wavelength meter provided an accurate wavelength value for the laser. Further, the fluorescence from a static iodine cell was monitored to facilitate the setting of the laser at the desired spectral position in the wing of the line and for monitoring possible frequency drifts. The main beam, which typically had a power of 100 mW, was alternately sent in opposite directions through the measurement region using a rotating sectorially aluminized quartz disc and a mirror arrangement. The experimental arrangement, in many ways, resemble that used in saturation or polarization spectroscopy [11]. The studied flow was generated in a small chamber with planar glass windows. The laser beams were directed by small 90° prisms in the chamber. A tapered glass tube with an orifice of 0.5 mm diameter was used to form a jet of seeded air in the chamber, which was evacuated by a rotary vacuum pump. I2 seeding was provided by passing air through a chamber at room temperature containing iodine crystals. The seeding fraction was estimated to be of the order of 100 ppm. In our first measurements fluorescence light from a small section along the laser beam was recorded by a photomultiplier tube. A lock-in amplifier was used for recording the modulation in the light intensity that was induced by the flow. Elastic scattering was eliminated by isolating the fluorescence light with a 0.5 m monochromator. Most of the measurements were performed in an imaging mode, in which LIF from the beam was imaged with a lens onto a linear diode-array detector, that was placed behind a suitably chosen filter. We used a Tracor Northern Model TN–1223–41G detector which has an area of 25 x 2.5 mm and 1024 individual elements. The detector is connected to a TN–1710 main frame, where the data are stored and some processing can be carried out. A more detailed description of the set-up and the measurements is given in [12].

4. Measurements

Before performing velocity measurements with the system the two laser beams were balanced to yield equal fluorescence intensities for a static gas. This could be accomplished since the flow chamber always contained I2 contamination providing a background I2 vapour pressure. Initially, we carried out point monitoring experiments using lock-in techniques in order to gain general experience with the method. However, we will here concentrate on the imaging measurements, since these are the ones of greatest interest. An example of a measurement is shown in Fig. 3. Here the laser was tuned to the wing of a B–X system rovibronic line at 5892.34 Å. In the upper part of Fig. 3 spatially resolved fluorescence light intensity along the laser beam is shown for one direction of the laser beam while below the corresponding recording for the opposite direction is given. The data collection time for each of the curves was 2.6 ms and the background pressure in the flow chamber was about 1 torr. The effect of the displacement of the Doppler profile is very clearly demonstrated. In the middle of the fluorescence streak an increase or a decrease in the intensity is obtained corresponding to the gas jet crossing through the laser beams at an angle of about 10 degrees. In the lower part of the figure a velocity profile is given as calculated from the recorded fluorescence distributions using eq. (5). The largest uncertainty in the velocity determination is due to the error in the estimation of the line-shape factor \( g(\nu)/(dg(\nu)/d\nu) \) at the measurement frequency. In the particular case shown the factor was determined by measurements on the low-pressure, static I2 cell included in the set-up. This was possible since the flow measurement was performed at a chamber pressure at which pressure broadening was negligible. In general, experimental line-shape factor determinations should be performed under identical conditions as in the flow. Since pressure as well as temperature might vary through the measurement region (in particular in reactive flows) the line-shape factor determination is the weakest point in the present technique. However, there are ways to circumvent this problem and in the next section we suggest improvements to the technique.

The good signal-to-noise ratio obtained even for a very short measuring time in the example discussed above is clearly related to the low pressure at which the experiment was performed. At
404 U. Westblom and S. Svanberg

Fig. 3. Fluorescence light spatial distributions for laser beams propagating from the left and from the right, and the velocity profile calculated from these distributions using eq. (5). The chamber background pressure was 1 torr and the recording time for each LIF distribution was 2.6 ms.

Fig. 4. (a) (bottom) Examples of spatially resolved fluorescence light distributions each recorded during 2.6 ms at 50 and 100 torr, respectively. (b) (top) Fluorescence light distributions for a different jet arrangement. Chamber pressure: 1 torr.

Fig. 5. Suggested techniques improvements illustrated for a point monitoring case. (a) Illustration how an internal velocity calibration can be obtained by using a fast small frequency modulation on the counter-propagating laser beams. (b) Illustration of the concept of single-beam spectroscopic velocity measurements utilizing both wings of the spectral line. (c) Illustration of laser frequency tracking for velocity measurements.

higher pressures quenching of the fluorescence light occurs because of collisional de-excitation. Examples of experimentally recorded fluorescence light spatial distributions for higher pressures are shown in Fig. 4(a). The signal-to-noise ratio can clearly be improved by increasing the measuring time, which for the recordings in Fig. 4 were as short as for the example shown in Fig. 3, i.e., 2.6 ms. In Fig. 4(b) recordings at 1 torr for a different jet arrangement are shown for comparison.

5. Suggested techniques improvements

As we have pointed out the largest uncertainty in the spectroscopic velocity-measurement method discussed in this paper is in the determination of the spectroscopic factor \( g(\nu) / (dg(\nu)/d\nu) \). This suggests that attempts should be made to measure the factor in real time for the molecules participating in the velocity measurement. This can actually be performed by shifting the laser frequency as is also being independently proposed by Hanson et al. [13]. The technique is illustrated for the point measurement case in Fig. 5(a). By introducing a small frequency modulation \( 2\Delta\nu \) in the laser a corresponding intensity modulation, \( 2\Delta I \), is obtained. This (fast) modulation is superim-
posed on the (slow) modulation $2\Delta f$ induced by the flow interacting with the two counter-propagating beams. The changing of laser frequency can be seen as an introduction of a known "artificial" velocity $\Delta v$ simply related to $\Delta f$ by eq. (2). Thus the unknown velocity can now be evaluated in terms of the measured quantity $I(v_2)/I(v_1)$.

We note, that since the measured quantity is a dimensionless ratio, the measurement is independent of light intensity and seeding variations. Linear imaging can be performed by using laser beams propagating from the left and right at unshifted and shifted laser frequencies. The frequency shift can be induced by using a piezo-electrically mounted end laser mirror or by Bragg-cell techniques. If the laser beam intensity is modulated due to the method of frequency modulation it is necessary to correct for LIF intensity variations due to beam-intensity variations.

3. From a practical point of view the use of two counter-propagating beams can sometimes be troublesome. The beams should have the same diameter and should be accurately overlapped in space. One of the directions might not be practically available, e.g., in head-on measurements of the flow out of a combustor. However, a single-beam version of this spectroscopic velocity measurement technique can be realised by noting that instead of switching beam directions for a fixed frequency in the one wing of a spectral line, the frequency of a single laser beam can be switched between the two wings of a spectral line as illustrated in Fig. 5(b). If we assume that the laser centre frequency is adjusted to yield the same fluorescence intensity from both wings for a static medium, a movement of the medium will be detected as a modulation of the LIF intensity as indicated in the figure. The technique can be combined with a faster small frequency modulation for evaluating the velocity in terms of an induced "artificial" velocity as described above. However, arrangements for shifting the fast modulation phase by $180^\circ$ in synchronism with the slow, large frequency modulation must be made if lock-in techniques are to be used. In a practical system a static $I_2$ cell should be included for frequency diagnostics, frequency locking and normalization purposes. However, to the outside world the measurement system only exhibits a single laser beam. Again linear velocity imaging is possible using sequential frequency switching of the laser. For a large-frame single-mode Ar$^+$ laser with lines coincident with $I_2$ lines the frequency shifts may be induced by mode-hopping. The free spectral range is typically 75 MHz and thus one mode hop is suitable for "artificial" velocity generation whereas about 10 mode hops would produce the switching between the two line wings. The piezo-electrically driven intra-cavity etalon is controlled using signals from a static, well-controlled $I_2$ cell.

4. If only point measurements are required one way of performing a single-beam velocity measurement is to readjust the centre frequency of a laser with an alternate-wing frequency modulation to a point where modulation from the moving sample disappears. The necessary frequency adjustment $\Delta v$ can be evaluated from the normalized modulation $(I(v_1) - I(v_2))/(I(v_1) + I(v_2))$ that now instead occurs from a static $I_2$ cell, that initially did not exhibit any intensity modulation. For this type of measurement an iodine line that broadens symmetrically should be chosen. The frequency tracking technique is illustrated in Fig. 5(c).

6. Discussion

The techniques that have been described in this paper and elsewhere [9] offer unique possibilities for imaging measurements allowing new types of spatial correlation measurements in turbulent flows. However, suitable seeding materials are rare and from a practical point of view are presently limited to Na and $I_2$. Na yields a strong fluorescence but is very reactive and cannot be used in the presence of oxygen. $I_2$ is also reactive but can be used in air. However, the much weaker specific fluorescence calls for rather high seeding levels. Clearly, strong signals are needed for accurate measurements during a short time interval. We have proposed improvements to the technique which should increase the reliability and ease of application considerably. However, the frequency modulation techniques require reliable diagnostics and some modification of the laser systems.

It would be very convenient to be able to use naturally occurring species for spectroscopic velocity measurements. In combustion regions with a high concentration of OH, this radical, which is accessible with a frequency-doubled single-mode dye laser, might be useful for velocity measurements but the sensitivity will be impaired by rather broad line profiles. Molecular oxygen excited in steps with pulsed lasers is presently being investigated as a possible candidate for spectroscopic flow studies [14].

Acknowledgement

This work was supported by the Swedish Board for Technical Development (STU).

References