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Flow Visualization in Gaseous Flows

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1.0 SUMMARY

This report summarizes a three-year research effort (April 1982 to May 1985) to establish techniques for visualizing velocity in gaseous flows. Two approaches were considered, both of which are capable of yielding velocity simultaneously at a large number of flowfield locations, thereby providing "images" of velocity. The first technique employed a laser to mar specific fluid elements and a camera to track their subsequent motion. Marking was done by laser-induced phosphorescence of biacetyl, added as a tracer species in a flow of N_2, or by laser-induced formation of sulfur particulates in SF_6-H_2-N_2 mixtures. The second technique was based on the Doppler effect, and used an intensified photodiode array camera and a planar form of laser-induced fluorescence to detect 2-d velocities of I_2 (in I_2-N_2 mixtures) via Doppler-shifted absorption of narrow-linewidth laser radiation at 514.5 nm.

2.0 RESEARCH DESCRIPTION

Detailed descriptions of most of our past work are already available in publications (see list in Sec. 4.0) and previous annual progress reports. Here we summarize the background for our work and describe our most recent efforts to establish Doppler-shift velocity visualization as a practical scheme for 2-d velocity imaging.

2.1 Background

An important goal in fluid mechanics and aerodynamics is the development of techniques for instantaneous measurements of <u>velocity fields</u> in gas flows with high spatial resolution. Such techniques would facilitate the experimental investigation of complex flow fields and provide the flow modeler with previously unavailable information, such as velocity gradients or vorticity. Optical methods are sought because of their potential for rapid and nonintrusive measurements. Three basic approaches for velocity field measurements are currently being pursued in various laboratories: laser marking, particle-based methods and laser-induced fluorescence.

In laser marking, fluid elements are marked at a discrete time and tracked with a camera. Laser-induced phosphorescence[1] (references are listed in Sec. 5.0) appears to be the most promising laser-marking scheme. Although it is applicable over a wide velocity range, its accuracy and spatial resolution are limited. Our work on laser marking is discussed in Ref. 1 (laser-induced phosphorescence) and Ref. 2 (laser-induced particulate formation).

Methods based on the seeding of particles such as particle tracking[3] and speckle velocimetry,[4] more precisely called particle image velocimetry,[5] offer potential for a large velocity range, but they involve complex data processing and fail in flows where particle lag is a problem or where the seeding of particles is not possible.

The third approach for velocity field measurements, and the one we have emphasized in our research, is based on the detection of laser-induced fluorescence from a Doppler-shifted absorption line (see

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Fig. 1).[6,7,8] The signal-to-noise performance of current detection
systems, together with the magnitude of the Doppler effect and the
widths of typical absorption lines, limits this technique to velocities
above 5 m/s for flow conditions of common interest. However, laser-
induced fluorescence offers the major advantage of direct measurements
of molecular velocities free of the uncertainties associated with the
use of particles. In a recent paper we have demonstrated that fast
recording can be achieved by replacing the time-consuming tuning over an
entire absorption line with a scheme based on a fixed laser frequency,[7]
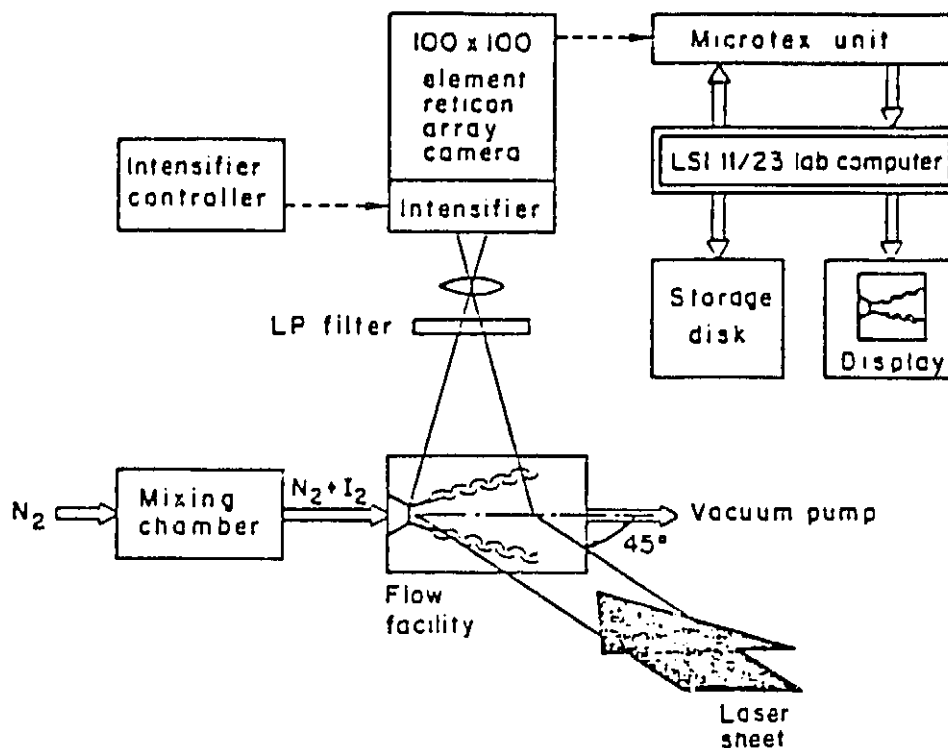which also simplifies greatly the data processing.

Figure 1: Sketch of typical excitation and detection set up for planar
laser-induced fluorescence showing the flowfield probed by a
thin sheet of laser light in the centerplane of the jet and
the camera imaging the fluorescence distribution perpendicu-
lar to the incoming sheet. For clarity, only one of the four
sheets is drawn.

2.2 Recent Research Developments

In this report we describe our most recent work to improve the Doppler-shift velocity visualization technique. The most significant change is that we now probe the flowfield with two fixed laser frequencies, so that the spatially varying slope of the absorption line can be measured directly at each point and no longer has to be computed assuming uniform line-broadening parameters throughout the flowfield. Furthermore, the directly determined slope provides additional information on the pressure distribution in the flow field. This suggests the possibility for combined measurements of velocity and pressure, which would provide a third major advantage over particle-based methods.

A similar setup is employed in all laser-induced fluorescence schemes; see Fig. 1. Gas molecules absorb incident radiation and subsequently emit fluorescence in all directions. In the case of field measurements, the exciting radiation is expanded into a sheet which is imaged onto a detector array, e.g. a photodiode-array camera. Each camera pixel thus receives fluorescence from a well-defined volume.

For narrow-bandwidth excitation, the number of photons absorbed in the volume V_c imaged onto a single pixel is given by:

$$N_{abs} = I \; n_{abs} \; V_c \; \frac{B_{12}}{c} \; g(\nu, P, T) \tag{1}$$

with:

I = incident laser intensity

n_{abs} = number density of molecules in the absorbing state

B_{12} = Einstein coefficient for absorption

g = line-shape function

The fluorescence signal S originating from this volume is proportional to the number of absorbed photons:

$$S = N_{abs} \; \frac{A_{21}}{A_{21} + Q_{21}} \; \left[\frac{\Omega}{4\pi} \; \eta_{coll} \right] \; R \tag{2}$$

4

with:

$A_{21}/[A_{21}+Q_{21}]$ = fluorescence efficiency

Ω = solid collection angle

η_{coll} = optical collection efficiency

R = responsivity of camera

In the following we show how this signal can be used to measure velocities via the Doppler effect. The component of the gas velocity in the direction of the exciting radiation u_l causes the gas molecules to absorb at a laser frequency which is Doppler-shifted from the original frequency ν by $\Delta\nu_{Dop}$:

$$\frac{\Delta\nu_{Dop}}{\nu} = \frac{u_l}{c} \tag{3}$$

where c is the speed of light. Four important considerations can now be noted:

1) In order to measure a second velocity component (and thus a two-dimensional velocity field) a second linearly independent beam direction is required.

2) The shift of the absorption line could be measured by tuning the laser frequency over the entire line and by simultaneously recording the fluorescence signal at each point of the flow field and in a static reference cell.[6] However, for rapid measurements a fixed laser frequency is desirable in order to reduce the data acquisition time. (The tuning itself can be done at kHz rates.)[9]

3) The laser frequency should preferably be fixed at the point where the fluorescence signal is most sensitive to Doppler shifts: the point of maximum slope of the absorption line.

4) In this case, the sensitivity is determined by the magnitude of the slope. For a given Doppler shift, a small slope results in a smaller change in absorption than a large slope. Since the slope depends on the line broadening which is independent of velocity but may vary spatially with pressure and temperature, an in situ determination of the slope is desirable.

These four considerations result in the illumination scheme sketched
in Fig. 2. Two directions, 0a and 1a, are necessary to probe the two
velocity components u_0 and u_1. The respective counterpropagating sheets,
0b and 1b, provide the capability to determine mean (unshifted) line-
shape values. The difference between the shifted line-shape values
for one direction is proportional to the Doppler shift in that direc-
tion with the slope as the scaling factor. By shifting the frequency in
direction 1 with respect to the frequency in direction 0 with an
acousto-optic modulator, the difference of the means (between directions
1 and 0) can be used to determine the slope. If the velocities are in
the range that permits the assumption of a constant slope, we can write:

$$\frac{\Delta v_{1,Dop}}{\Delta v_{AO}} = \frac{\text{g difference, direction 1}}{\text{difference between means}} = \frac{g_{1b} - g_{1a}}{[g_{1a} + g_{1b}] - [g_{0a} + g_{0b}]} \tag{4}$$
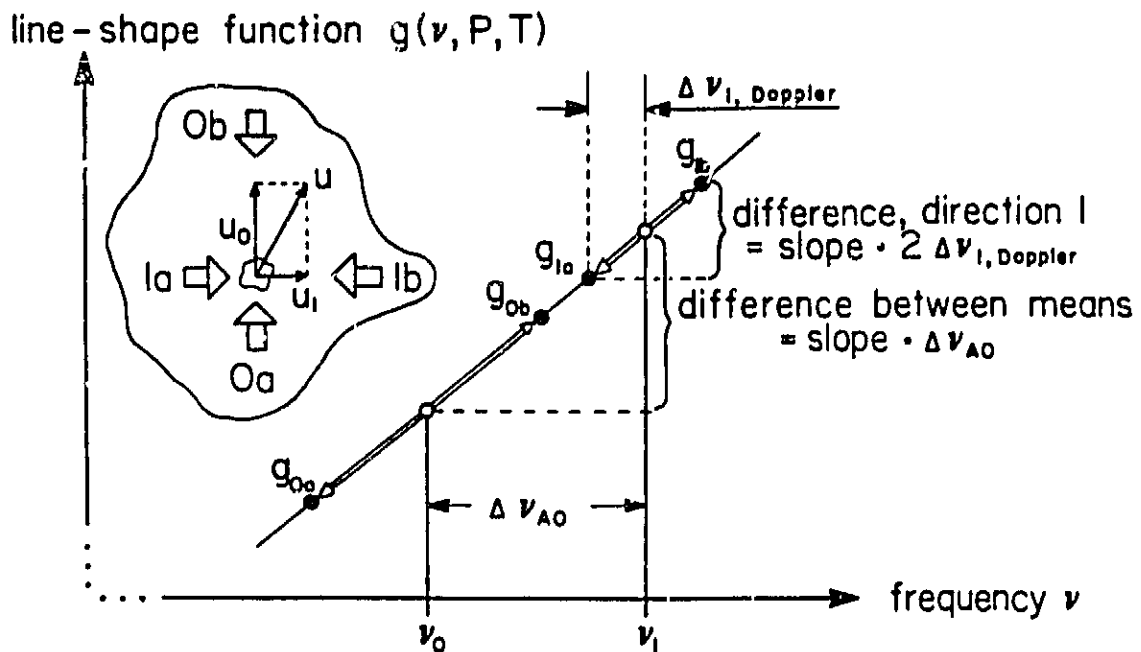

line-shape function $g(v, P, T)$

Figure 2:   By exciting a fluid element with two pairs of counter-propa-
gating beams (to probe the two velocity components u_1 and u_0)
at two different frequencies, the slope of the line can be
expressed in terms of values of the line-shape function. The
difference in line-shape functions in any one direction is
proportional to the corresponding velocity component. Δv_{AO} is
the frequency shift provided by an acousto-optic modulator.

6

Since fluorescence signals – not line-shape values – are measured, eq. (4) has to be rewritten using equations (1) and (2). If the properties of the flow remain constant during the measurement time interval, all factors cancel out except for the laser intensity which depends on the nonuniform power distribution in each individual laser sheet. Incorporating also eq. (3), velocity component u_1 is given by:

$$u_1 = \frac{c}{\nu} \Delta \nu_{AO} \frac{S/I_{1b} - S/I_{1a}}{[S/I_{1a} + S/I_{1b}] - [S/I_{0a} + S/I_{0b}]} \tag{5}$$

and the measurement is seen to be self-calibrating. The spatially varying laser intensities are recorded on static frames prior to the experiment.

It is important to appreciate the advantage of employing relative measurement techniques in avoiding the need to know the local quenching rate (term Q_{21} in the Stern-Vollmer factor) and number density. A similar strategy is used in two-line schemes for temperature measurements.[10]

The experimental setup is shown in Fig. 3. The 900 mW single-mode output of a Spectra Physics Model 171 argon ion laser was sent through an Isomet 1205C acousto-optic modulator which served two purposes: splitting the beam and shifting the frequency of the first-order deflected beam by 100 MHz. Two subsequent beam splitters generated the respective counterpropagating beams. Each of the beams was expanded into a sheet and delivered a power of 100 $\pm$ 10 mW with a width of 21 mm (measured at the half power point) and a thickness of 150 μm (Rayleigh range 30 mm).

An oven-stabilized intra-cavity etalon was used to select an axial mode near the point of maximum slope in the wing of the overlapping P(13)/R(15) lines of the I_2 (43,0) band of the B-X electronic system under the argon ion gain profile at 514.5 nm. The single-mode behavior was checked with a scanning interferometer.

The laser frequency was set by tilting the intra-cavity etalon until the lock-in-amplified static fluorescence signal, normalized by the

single-mode argon laser

intracavity etalon

scanning interferometer

oscilloscope / mode structure

same pressure as flow chamber

static cell

photodiode

chopper

lock-in amplifier

A

A/B

B

digital voltmeter / normalized fluorescence

photodiode

digital oscilloscope / laser power

ν_0

acousto-optic modulator

ν_0 ν_1

chopper

pulse transformer

pulse delay generator

gate trigger for intensifier / frame trigger for digital camera
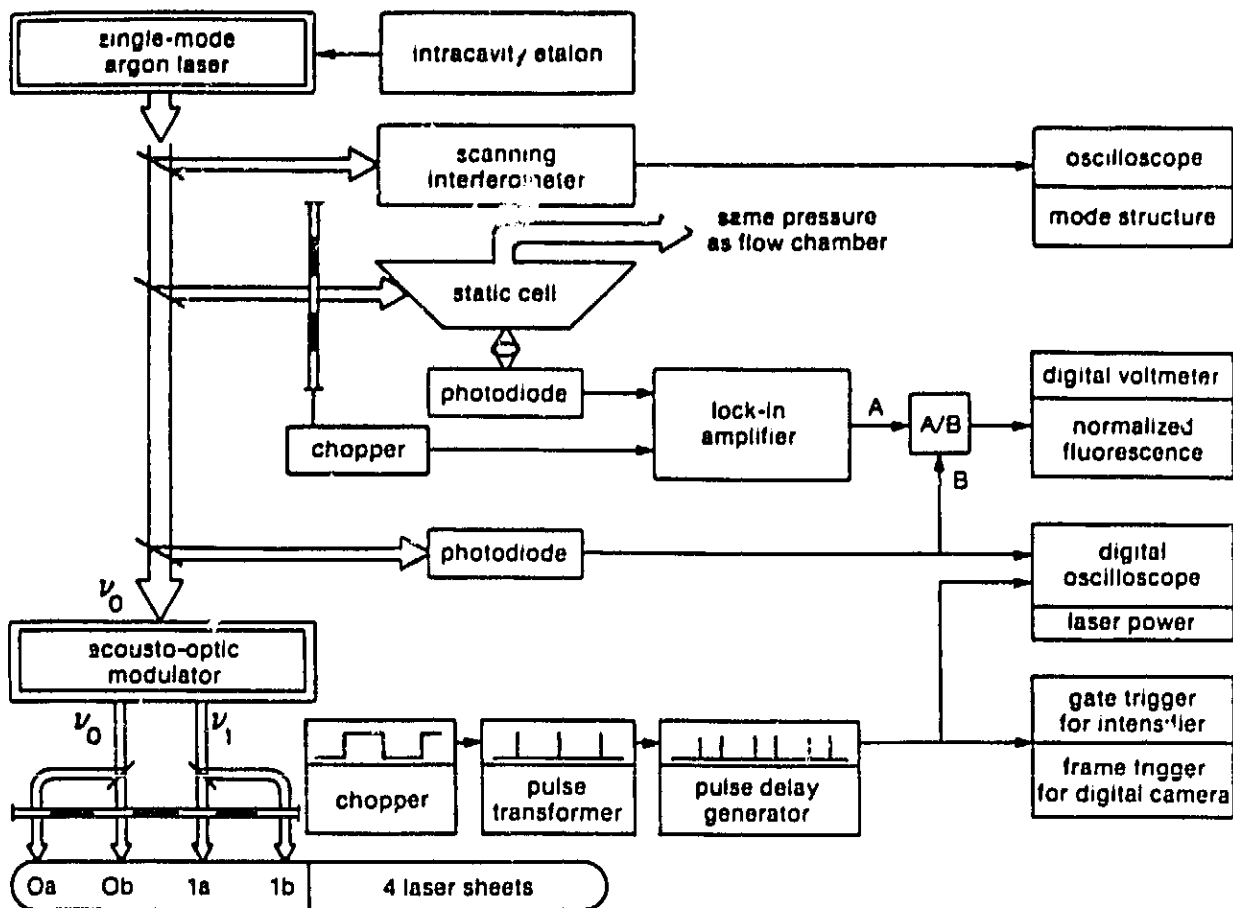
Oa Ob 1a 1b 4 laser sheets

Figure 3: Experimental setup picture showing the laser beam path (double line) and the electronic processing (single lines). The scanning interferometer monitors the axial mode structure of the argon ion laser. The static cell in connection with the photodiode gives a normalized fluorescence signal. The laser power is monitored on a digital oscilloscope. The chopper selects one laser sheet at a time and provides the triggering signal for camera and intensifier.

laser power, assumed the value corresponding to the point of maximum slope. This point was found prior to the experiment by tuning over the absorption line at the same background pressure.

One of the four laser sheets was sequentially selected by a chopper. A synchronized signal from the chopper was pulse-transformed and delayed to provide a frame trigger for the digital camera and the gate trigger

for the image intensifier. Additionally this signal triggered a Nicolet digital oscilloscope used to check the fluctuations of the laser power, which proved to remain below 1%.

The redshifted broadband fluorescence was imaged through a 540 nm long-pass filter (to block scattered light) onto a 100x100 photodiode array camera (Reticon RS520), which was lens-coupled to a Varo single micro-channel plate intensifier. Four successive camera frames were stored in the buffer of an Microtex 7402 camera-computer interface and subsequently processed by an LSI 11/23 laboratory computer.

To illustrate the technique, the simple two-dimensional velocity field in the center plane of a subsonic round jet has been measured. Molecular iodine was seeded at a level of 300 ppm in the nitrogen buffer gas, which ensured optically-thin behavior. The flow-field geometry and the results for the axial velocity component are shown in Fig. 4. Relatively long integration times of 250 ms per frame were necessary due to inefficient lens-coupling of the intensifier to the camera. In this case, the accuracy is limited by the integratable thermal electronic noise (Johnson noise) to 5 m/s (corresponding to 7% of the maximum velocity). More efficient fiber-coupling to an array equipped with a fiber window would allow shot-noise-limited detection and an increase in the framing rate by a factor of 100 giving overall measurement times of 10 ms assuming the same photon flux. Even shorter recording times would be possible with higher laser powers.

An exciting possibility is suggested by the fact that the slope of the line-shape function can now be measured in situ. In particular, the ratio of the function and its slope, available from the average of the mean signals, and the difference between the mean signals,

$$\frac{g}{dg/d\nu} = \frac{\Delta\nu_{AO}}{2} \frac{\left[S/I_{1a} + S/I_{1b}\right] + \left[S/I_{0a} + S/I_{0b}\right]}{\left[S/I_{1a} + S/I_{1b}\right] - \left[S/I_{0a} + S/I_{0b}\right]} , \tag{6}$$

is a quantity which depends primarily on pressure for this absorption line near room temperature, as shown in Voigt line-shape calculations using known broadening parameters (Fig. 5). The measured values for the
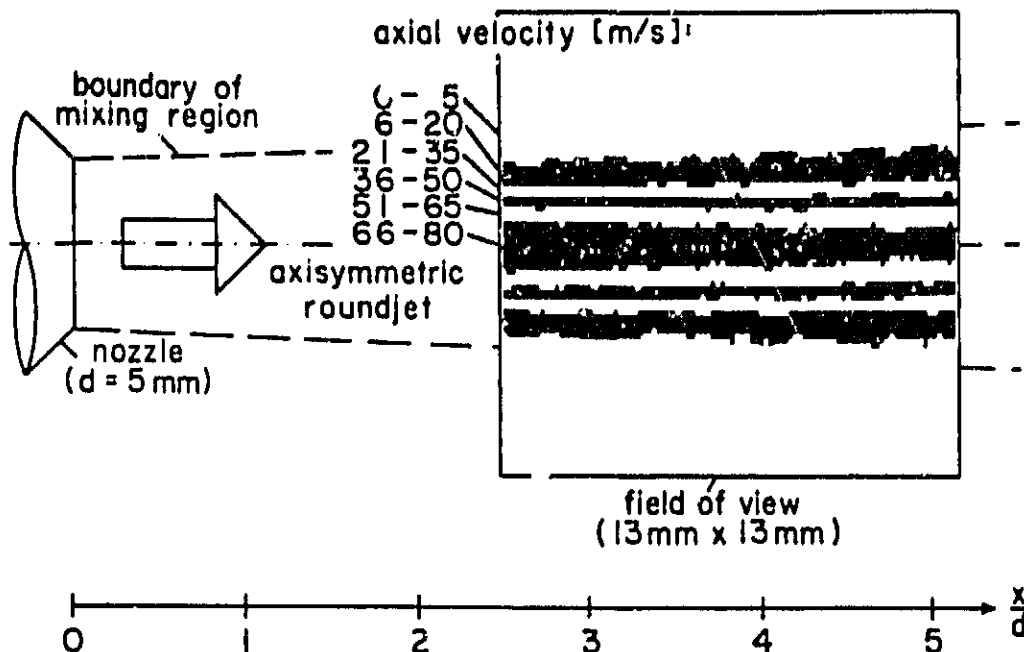
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axial velocity [m/s]

boundary of
mixing region

0 - 5
6 - 20
21 - 35
36 - 50
51 - 65
66 - 80

axisymmetric
roundjet

nozzle
(d = 5 mm)

field of view
(13mm x 13mm)

0   1   2   3   4   5 $\frac{x}{d}$

Figure 4: Sketch of the geometry of a subsonic round jet and laser-
induced fluorescence results for the axial velocity in the
field viewed by the camera. Alternate black and white bands
are used to emphasize different velocity regimes. The back-
ground pressure is 35 Torr at room temperature. The Reynolds
number is 1100, based on the nozzle diameter of 5 mm.
Spatial resolution is $(150 \ \mu m)^3$ per pixel, temporal
resolution is 1 s.

present incompressible flow field are nearly constant as expected and
lie within the error margins imposed by the accuracy of the detection
scheme employed. The proposed method has important potential, however,
for spatially and temporally resolved combined measurements of velocity
and pressure fields in compressible flows, where changes in pressure are
significant and the perturbing effect of pressure probes is undesirable.
This may be an important first step toward direct combined measurements
of the pressure and velocity gradient terms of the Navier-Stokes equa-
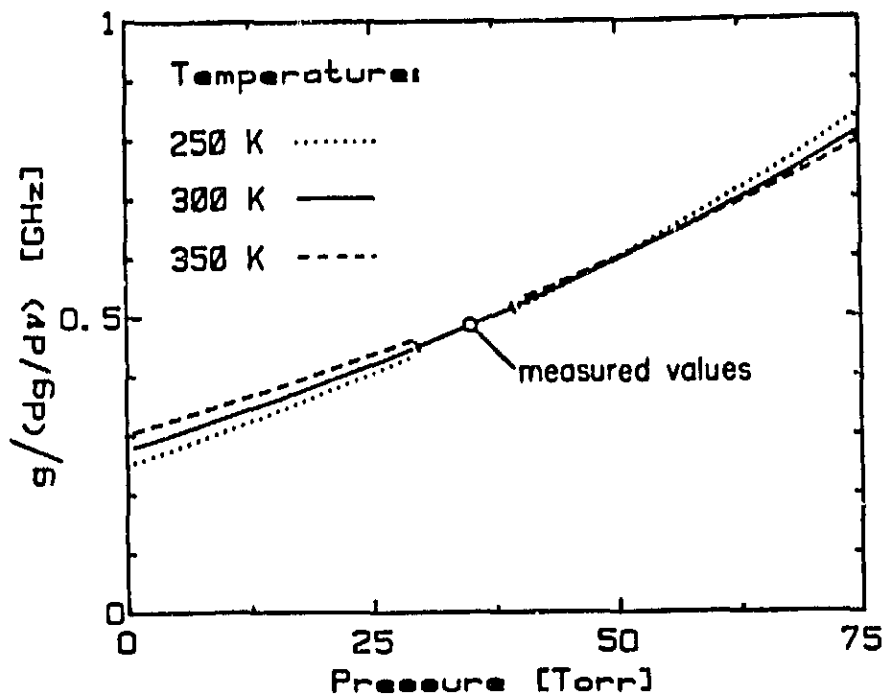tions.

Figure 5: The function g/(dg/dν) computed from broadening parameters is only weakly temperature dependent and can be used as a calibration curve for pressure measurements. These curves were calculated for a laser frequency fixed at the point of maximum slope for a background pressure of 35 Torr. The 35-Torr point is reproduced by the fluorescence values measured in the flow.

3.0 PERSONNEL AND FACILITIES

This research program was carried out under the direction of Professor Ronald K. Hanson and involved two Graduate Research Assistants in Mechanical Engineering, Bernhard Hiller and Chris Hassa. The contributions of Dr. James McDaniel in the early phase of this program are also gratefully acknowledged. All these individuals are affiliated with the High Temperature Gasdynamics Laboratory, which is a major research and educational laboratory within the Mechanical Engineering Department. This laboratory has been involved for more than twenty years with research on reaction kinetics, modern diagnostics, combustion, and on the dynamic behavior, electrical properties and applications of high-temperature gases.

4.0 PUBLICATIONS

Five publications have resulted from this research program:

1. J.C. McDaniel, B. Hiller and R.K. Hanson, "Simultaneous, Multiple-Point Measurements of Velocity Using Laser-Induced Iodine Fluorescence," Optics Letters 8, 51 (1983).

2. B. Hiller, J.C. McDaniel, E.C. Rea, Jr. and R.K. Hanson, "Laser-Induced Fluorescence Technique for Velocity Field Measurements in Subsonic Gas Flows," Optics Letters 8, 474 (1983).

3. B. Hiller, R.A. Booman, C. Hassa, and R.K. Hanson, "Velocity Visualization in Gas Flows Using Laser-induced Phosphorescence of Biacetyl," Rev. Sci. Instrum. 55, 1964 (1984).

4. C. Hassa and R.K. Hanson, "Fast Laser-induced Aerosol Formation for Visualization of Gas Flows," Rev. Sci. Instrum., in press.

5. B. Hiller and R.K. Hanson, "Two-frequency Laser-induced Fluorescence Technique for Rapid Velocity Field Measurements in Gas Flows," Optics Letters 10, 206 (1985).

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10. M. Alden, P. Grafström, H. Lundberg, and S. Svanberg, "Spatially Resolved Temperature Measurements in a Flame Using Laser-induced Two-line Atomic Fluorescence and Diode-array Detection," Opt. Lett. 8, 241 (1983).

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16. Abstract

This report summarizes a three-year research effort (April 1982 to May 1985) to establish techniques for visualizing velocity in gaseous flows. Two approaches were considered, both of which are capable of yielding velocity simultaneously at a large number of flowfield locations, thereby providing "images" of velocity. The first technique employed a laser to mark specific fluid elements and a camera to track their subsequent motion. Marking was done by laser-induced phosphorescence of biacetyl, added as a tracer species in a flow of N_2, or by laser-induced formation of sulfur particulates in SF_6-H_2-N_2 mixtures. The second technique was based on the Doppler effect, and used an intensified photodiode array camera and a planar form of laser-induced fluorescence to detect 2-d velocities of I_2 (in I_2-N_2 mixtures) via Doppler-shifted absorption of narrow-linewidth laser radiation at 514.5 nm.

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