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# Techniques for high-speed digital imaging of gas concentrations in turbulent flows

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**Abstract.** Techniques have been developed to measure the concentration of nozzle gas quantitatively in transitional and turbulent flow regimes at high framing rates in two dimensions. Elastically scattered light from a seeded jet, illuminated by a sheet of laser light, was recorded in three ways. The first involved the use of a rotating mirror to sequentially place images onto different portions of a relatively slow vidicon-based imaging system to achieve a high effective framing rate (2–10 kHz) for up to four frames. The second used a portion of a monolithic 128×128 photodiode array connected directly to a high-speed analog to digital converter to achieve a framing rate of 1.136 kHz. The third used a fast video camera and recorder (6 kHz) to store images on magnetic tape in analog form, which were later digitized upon playback. A comparison of these techniques is presented along with a discussion of factors important in the use of high-speed digital imaging systems. It is shown that the temporal development of large-scale structures can be digitally recorded in two dimensions, with the advantage of being both quantitative and visually interpretable.

## 1 Introduction

The importance of large-scale structures in turbulence has prompted the development of several new experimental techniques for their quantitative characterization. Instantaneous nozzle gas concentration fields have been mapped by detecting the elastically scattered light from an aerosol laden flow (Long et al. 1981). Similarly, other light scattering processes have been used for two-dimensional mapping of structures within turbulent flows, including Rayleigh scattering from gas molecules (Escoda & Long 1983), fluorescence (Dyer & Crosley 1982), and Raman scattering (Long et al. 1983 a). While the information provided by these techniques is valuable, the detectors used do not allow images to be recorded at a rate high enough to observe changes from one frame to the next. It is consequently difficult to extract information on the evolution of these structures.

One means of gathering information on this evolution, even with slow measurement techniques, is to study externally forced flows. Under certain conditions, an external perturbation will cause the flow to evolve deterministically (Crow & Champagne 1971). By making measurements at varying time delays, it is possible to see the temporal development of the regular structures. Two-dimensional imaging has been shown to give information on the evolution of structures in acoustically forced flows (Long et al. 1983 b) and in photoacoustically perturbed flows (Fourguette & Long 1983). A similar approach is also applicable to flows that have cyclic characteristics such as in internal combustion engines or pulsed combustion systems. For example, Cattolica and Vosen (1984) have used fluorescence imaging to demonstrate the development of structures in an impulsive jet.

High-speed imaging systems must be used in the general study of large-scale structures. A number of high framing-rate film cameras are available that have been valuable in flow visualization (Merzkirch 1974). Film-based systems have several drawbacks, however, including the lack of real-time playback capability, limited dynamic range, and nonlinearities associated with the film itself. These considerations indicate the need for electronically based systems capable of high framing rates, directly quantifiable output, and real-time data display. Advances in electronic detectors, image intensifiers, lasers, and computer systems have brought such systems closer to realization. At present, however, no single system has all the desired characteristics.

Some optical techniques have been demonstrated that give quantitative information on the temporal evolution of structures in turbulent flows. For example, a rotating mirror has been used to record the evolution of structures in one dimension at successive times (Long et al. 1981). More recently, image pairs of OH fluorescence obtained in rapid succession have been recorded in two dimensions by using an oscillating mirror with a double-pulsed Nd:YAG laser (Dyer & Crosley 1984).

Fast electro-optical data acquisition schemes have great potential in experimental fluid mechanics. By directly digitizing images consisting of many points at a high repetition rate, one can determine such quantities as convection velocities, intermittency factors, and the mixing undergone by a given structure as it travels downstream. With equipment currently available, however, certain compromises are necessary in spatial resolution, low-light sensitivity, dynamic range, and framing frequency. The important factors in digital imaging are presented below together with three different approaches to high-speed digital imaging. The advantages and disadvantages of each technique are discussed.

## 2 Digital imaging considerations

Several electronic imaging systems that may be used for flow diagnostics are now available. Vacuum tube based systems, used in television, are currently the most mature of the imaging technologies. However, rapid improvements in semiconductor fabrication have led to the availability of several solid-state detectors. In selecting a system for use in digital imaging experiments, a number of factors must be considered (Kychakoff et al. 1984). Among these are:

### *2.1 Sensitivity*

The sensitivity required for an experiment depends on both the illumination source and the light scattering mechanism utilized. For very weak optical signals, currently available detectors may not have the sensitivity required. It may, however, be possible to couple the detector to an image intensifier to augment the overall gain (Snow et al. 1986). When this is done, another element is added to the system and the characteristics of the intensifier must also be taken into account in the overall system performance.

### *2.2 Dynamic range*

The dynamic range of a detector is defined as the ratio of the highest and lowest intensity features that can be linearly monitored in a single frame. Values range from less than 100 to more than 5,000 for different types of detectors and also vary somewhat between detectors of a given type. The available dynamic range often falls as the framing rate is increased. The addition of an image intensification stage to increase sensitivity may also reduce the dynamic range.

### *2.3 Framing rate*

The framing rate required to follow the temporal evolution of a flow depends critically on the flow itself. Standard television systems have framing rates of 60 Hz which may be useful for some low-speed flows. However, this is clearly not fast enough for most gas-phase flows which often require framing rates in the kHz range. Television-based systems incorporating a scanning electron beam to read the image data (e.g., vidicon systems) are not good for continuous high-speed applications, principally because of the "image lag" (the inability to completely read in a single scan the signal stored on the target). Thus, even if the electron beam scanning rate were greatly increased, the effective framing rate would remain low since many more scans would be required to completely read the signal from the previous image.

Solid-state imaging systems such as charge-coupled devices (CCD's), diode arrays, or charge-injection devices (CID's) have much more promise for high-speed imaging. The lag problem associated with the older vacuum devices is not present here because of the different way in which the signal is read out. However, as with the older vacuum tube detectors, most of these devices read the signal serially. The pixel read-out rate of present detectors can be up to $\sim 20$ MHz.

### *2.4 Resolution*

The detector resolution (the size of the pixel array) and the spatial resolution desired must be taken into account in the design of the experiment. The spatial volume associated with each pixel can be varied by proper selection of the optics used to image the region studied. For high framing rates, increased resolution may not always be desirable since the pixel rate must be increased in order to maintain a given framing rate. In addition, for high resolution images, the problems associated with data storage and analysis can be overwhelming.

### *2.5 Data corrections*

Any detector has associated with it a certain "fixed pattern noise" which corresponds to the signal recorded when no light is incident on the detector. This can arise from slight differences in the characteristics of individual imaging elements of the detector and from thermally generated noise. There may be additional background signal due to stray light scattered from the surroundings. To correct for these effects, it is necessary to obtain a background signal such that all aspects of the experiment are the same as when data are actually taken, except that the signal is missing.

Another correction relates to nonuniformities in the response of the detector and the imaging system. Such corrections must usually be applied to digital images in order to obtain quantitative information. The gain of a two-dimensional detector may vary somewhat as a function of position across the detector. This is particularly prevalent in systems utilizing vacuum tube technology or in systems using electrostatically-focused image intensifiers. In order to correct for this, an image should be recorded of a field of constant intensity, thereby recording the response of the system. The dark-field background should then be subtracted from this image and the background-subtracted data should be divided by the resulting response image. Note that, even if the gain of the detector were absolutely constant, this correction step would be needed to correct for vignetting in the imaging optics and nonuniformities in the intensity distribution of the illumination source.

Using the corrections outlined above, the desired intensity function, $I(x,y)$, is obtained as follows:

$$I(x,y) = [S(x,y) - B(x,y)]/[R(x,y) - B(x,y)]$$

where $S(x,y)$ is the raw signal recorded from the experiment, $B(x,y)$ is the background signal, and $R(x,y)$ is the constant-intensity response signal.

### 2.6 *Data format*

The format used to store the data must be well chosen because these imaging experiments are capable of producing a large volume of data in a very short time. The most attractive alternative is to immediately digitize the data and store it in the memory of a computer. Although this approach is feasible, it requires fast analog-to-digital conversion and a large high-speed, multi-ported memory (standard memory devices are not capable of receiving data at the 5–20 MHz rate required). Another approach is to store the information in analog format and perform the digital conversion later at a slower rate.

## 3 Lorenz-Mie scattering

In each of the experiments described below, the Lorenz-Mie scattering technique has been used to determine the gas concentration in a nonreacting flow. This technique is based on the fact that, for a gas seeded uniformly with aerosol particles, the intensity of the elastically scattered light from the aerosols is proportional to the concentration of the seeded gas (Becker 1977). If the seeded gas mixes with a second unseeded gas, the number of scattering particles is less in that given volume and proportionally less radiation is therefore scattered. The technique was first used to measure concentrations at a single point (Rosensweig et al. 1961). Since then, it has been extended for two-dimensional mapping using a thin sheet of laser light as the illumination source.

Although the Lorenz-Mie scattering technique does not require that a laser be used as the light source, laser light is desirable because of its spatial coherence and intensity. Many commercially available lasers can be used for flow imaging experiments with the selection of a particular laser depending on the light scattering mechanism to be used, the laser energy required, and the quantities to be measured. For high-speed imaging, pulsed lasers that provide high single-pulse energy and high repetition rates are preferred. Recently, several new lasers with such characteristics have become available. Particularly attractive are excimer lasers capable of pulsing at up to 1 kHz and copper vapor lasers with a pulse repetition rate of up to ~ 6 kHz (Grove 1982).

## 4 Segmented digital imaging

Figure 1 shows the schematic representation of a technique employing a rotating mirror to place four consecutive rectangular images of an aerosol seeded jet onto the

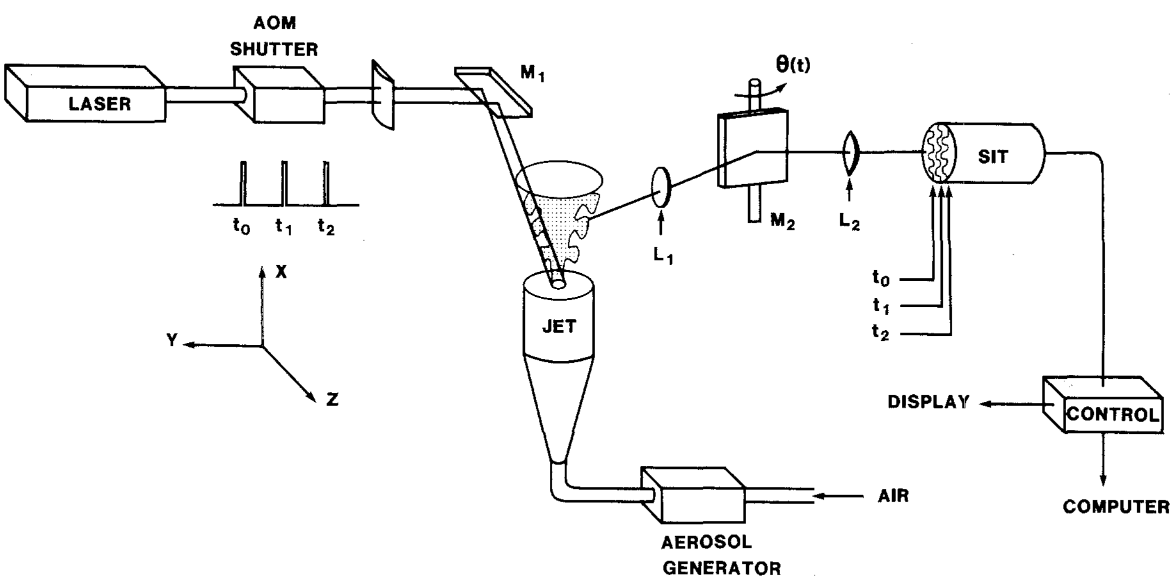


**Fig. 1.** Experimental setup for recording four consecutive concentration measurements of the mixing region of a jet. Rotation of the mirror is synchronized with the pulsing of the laser using an acousto-optic modulator (AOM). The image of the jet is displaced across the face of the detector between pulses

face of a single low-light-level optical multichannel analyzer. Air was seeded with submicron sized aerosol particles using an atomizing aerosol generator (Sierra Instruments Model 7330). The seeded nozzle gas then passed through a 4 mm diameter axisymmetric nozzle. A sheet of light from an $Ar^+$ laser (1 W at 514.5 nm) was focused into a plane that intersected the mixing region of the jet. The scattered light was collected by one lens, reflected from the rotating mirror, and focused onto the detector by a second lens so that the image occupied one quarter of the scanned area of the detector. In order to freeze the motion of the flow, the laser was gated on for a short time (50 µsec) every 450 µsec, using an acousto-optic modulator. When the rotation of the mirror was synchronized with the scanning of the camera and the pulsing of the laser, four separate sequential images of the flow were recorded. The effective frame rate for the four images recorded was 2 kHz. The mirror could have been rotated much faster to achieve framing rates up to 10 kHz.

In this experiment, the four images were effectively stored on the face of the low-speed camera in analog form until they could be read out slowly at a later time. The camera was a silicon intensified target (SIT) vidicon detector (PARC Model 1254) which is designed to be directly interfaced to a computer via a digital controller (PARC Model 1216). The computer controls the scan format (selected to be $100 \times 100$ pixels for the data shown here) and receives the digitized data. Although this camera requires about one second to digitize a single frame, the rotating mirror scheme makes it possible to achieve a high effective framing rate for the four images stored. The SIT vidicon provides a greater dynamic range ($\sim 1{,}000$) than other imaging devices used in this study and, since this detector incorporates an intensification stage, the low-light sensitivity is quite good. The amount of laser energy required to obtain the data shown was 50 µJ (1 W for 50 µsec).

Figure 2 displays temporally correlated data from the mixing region of a turbulent jet collected at 2 kHz. The Reynolds number based on nozzle diameter (4 mm) is 2,200 and the region observed is from 1.5 to 8 nozzle diameters downstream.

The raw data have been corrected for background light and nonuniformities in the response of the camera and the illumination sheet, as described in the previous section. A dark background was recorded in the absence of the seeded jet. A cuvette containing a fluorescent dye solution was then placed at the location filling the image frame to illuminate uniformly each of the four positions on the camera face. The data were then divided by this image to correct for the nonuniformities in the camera, the illumination sheet, and the collection optics.

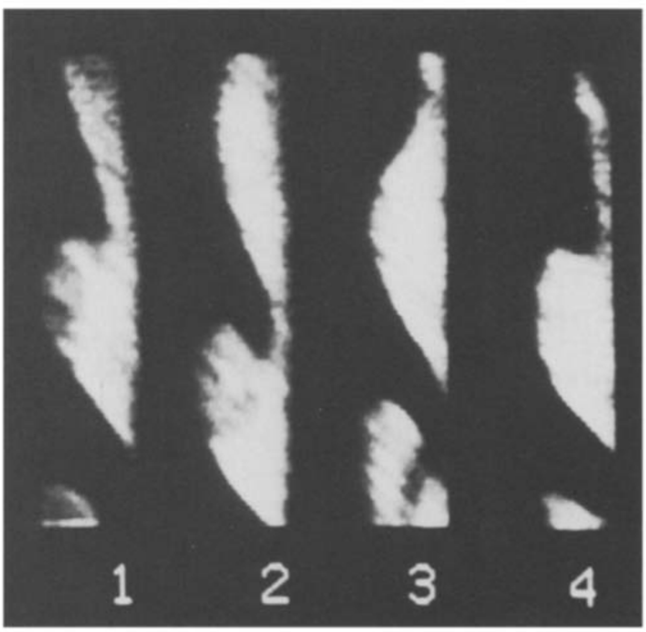


**Fig. 2.** A set of four concentration measurements produced at 2,000 frames per sec. The flow direction is from top to bottom and the time sequence progresses from left to right. The flow rate is 8.24 m/sec from a 4 mm diameter nozzle corresponding to a Reynolds number of 2200. The region of observation is from 1.5 to 8 diameters downstream. Lighter regions in the figure denote higher concentration of nozzle gas

## 5 Continuous digital imaging

The experimental setup is shown schematically in Fig. 3. The nozzle gas was seeded as described above and a 4 mm diameter axisymmetric nozzle was again used.

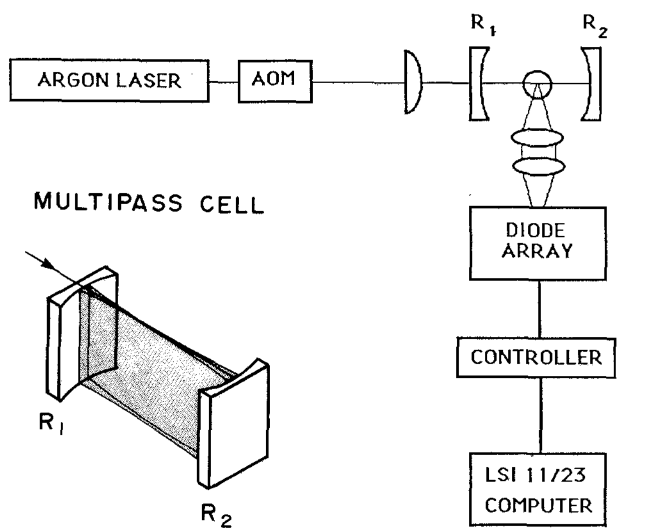


**Fig. 3.** Experimental configuration used for continuous two-dimensional concentration measurements at 1.136 kHz. The $Ar^+$ laser is pulsed using an acousto-optic modulator (AOM) which is synchronized with a photodiode array. The beam is formed into a thin sheet and the scattered light from the jet is proportional to the nozzle gas concentration. The optical reflectors ($R_1, R_2$) used to form the multipass cell are shown in detail

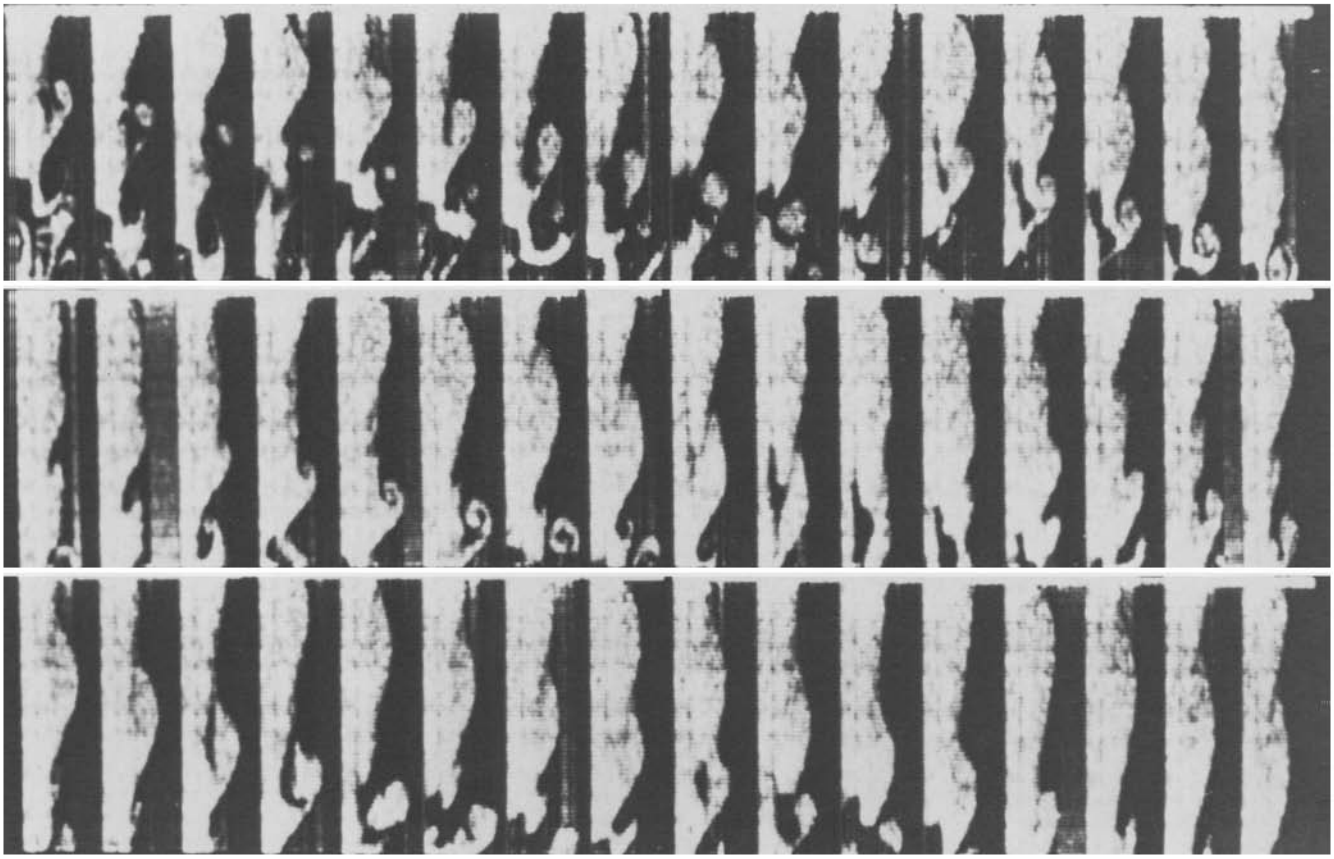

**Fig. 4.** A sequence of nozzle gas concentration measurements recorded at a framing rate of 1.136 kHz. The flow proceeds downstream from 4 nozzle diameters (top) to 7.5 diameters (bottom) at a rate of 3.4 m/s, yielding a Reynolds number of 900. The sequence goes from left to right and then top to bottom. Lighter regions correspond to higher concentrations of nozzle gas

An $Ar^+$ laser operated on all lines was pulsed using an acousto-optic modulator, then focused into a sheet that illuminated an axial slice of the jet. The sheet of light was formed by passing the laser beam back and forth repeatedly between two opposing cylindrical reflectors, as shown in the figure.

A region 14.5 mm × 14.5 mm was imaged onto the photodiode array of a Reticon MC9128 camera, using two camera lenses. The camera was interfaced directly to an LSI 11/23 computer using a camera/computer interface (Microtex 7402) with 1.25 Mbytes of high-speed memory. The pixel rate was 8 MHz and, through software control, the user could designate the array width to be used (the number of pixels). When scanning the full 128 × 128 photodiode array, the detector could be operated at a framing rate of ~ 0.4 kHz and a total of 80 frames could be collected in one data acquisition sequence. A much higher framing rate was necessary for the flow conditions considered here. To accomplish this, the array was operated in a 128 × 32 pixel format which allowed for storage of 320 consecutive images. The data in Fig. 4 were collected at 1.136 kHz. The nozzle flow velocity is 3.4 m/sec, corresponding to a Reynolds number of 900. The region shown is from 4 to 7.6 nozzle diameters downstream. The pulse duration used here was 67 μsec with the laser operating at 5 W.

The raw data collected by the camera have been corrected for background light and nonuniformities in the response of the camera and the illumination sheet, as described above. A dark background was recorded in the absence of the seeded jet. The response of the system was recorded by filling the entire image frame with a seeded gas that was passed through a large nozzle positioned directly into the sheet of light and then averaged over several realizations. The data were then divided by this image to correct for the nonuniformities in the camera, the illumination sheet, and the collection optics.

Since this diode array camera was not intensified, the sensitivity of this detector was less than that of the SIT vidicon used in the previous experiment. Further, the dynamic range of this detector is specified to be 100 which is an order of magnitude less than that discussed previously. The advantages of this system are in the large sample size and in the flexibility of data storage format.

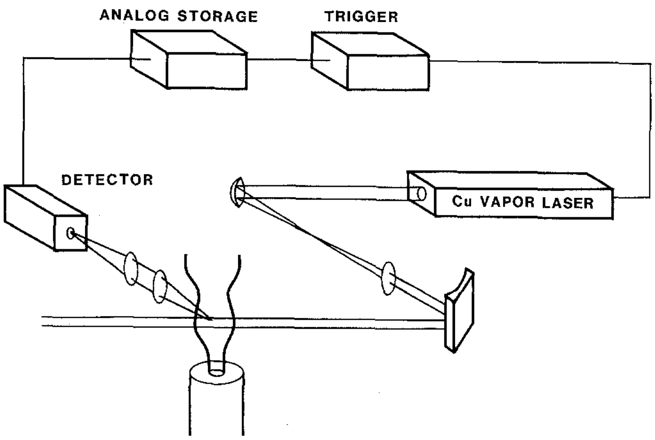


**Fig. 5.** Experimental configuration used for high speed video recording. A copper vapor laser is pulsed at 6 kHz and synchronized with a high-speed video camera which records the motion of the flow

## 6 High-speed video recording

A high-speed video recording system (Spin Physics SP2000) was used with the experimental setup shown in Fig. 5. A copper vapor laser (Plasma Kinetics Model 451) was used to form a sheet using the emission at both the 510 and 578 nm lines and pulsed at a rate of 6 kHz. The image sensor contains $192 \times 240$ pixels and is capable of a data rate of $10^8$ pixels per sec. To achieve this rate, a new parallel-serial hybrid video format is used in which six separate blocks of 32 pixels are read. With this configuration, a maximum full-frame rate of 2 kHz can be obtained. The camera can be operated in a mode in which only part of the detector is scanned, allowing the user to sacrifice some of the spatial resolution to achieve a faster framing rate. We used two of the six blocks for data acquisition at 6 kHz. To compensate for the loss of spatial resolution, only half of the jet was imaged onto the array.

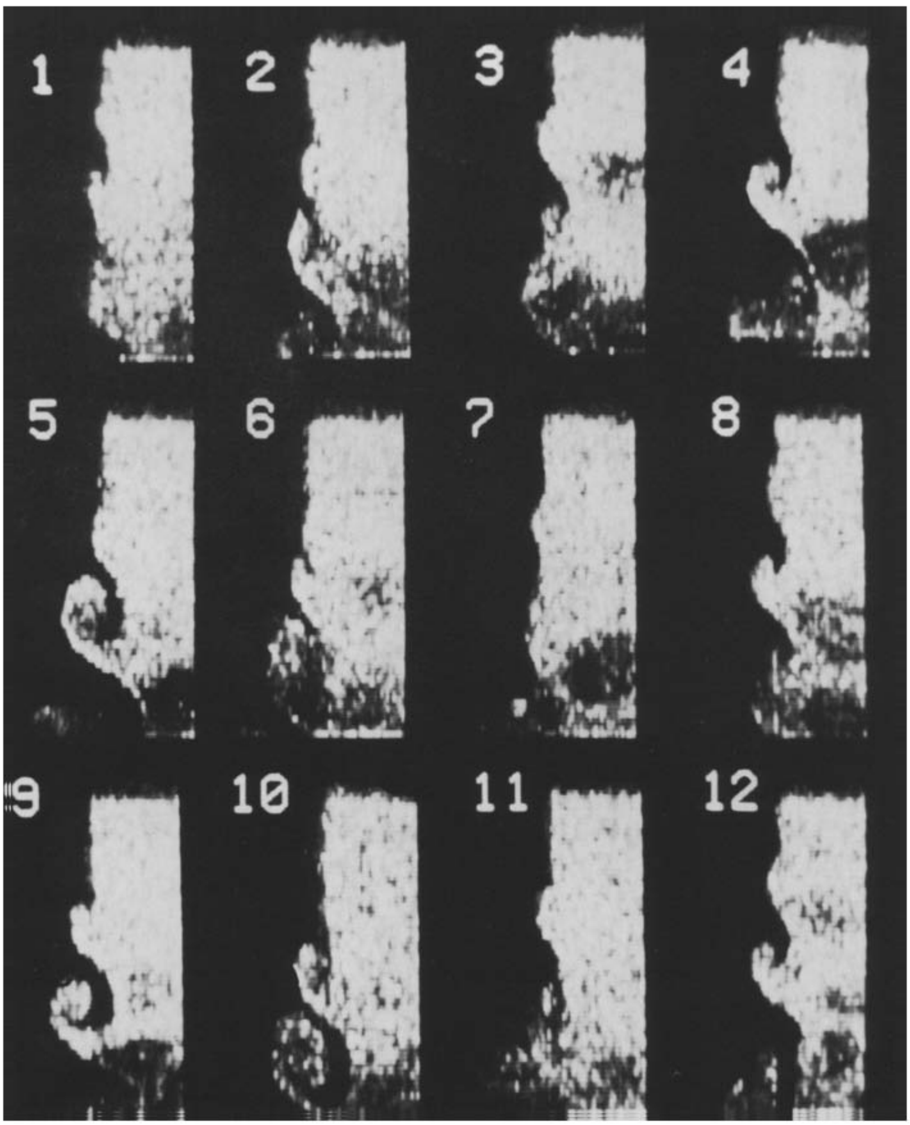


**Fig. 6.** Concentration measurements performed at a 6 kHz framing rate. These images were first recorded by a video system and then digitized. The flow rate is 17.3 m/sec from a 2 mm nozzle, corresponding to a Reynolds number of 2310. The flow progresses from top to bottom with the region of observation approximately 1 to 7 nozzle diameters downstream. The shading levels correspond to different nozzle gas concentration with the lighter regions representing higher nozzle gas concentrations

The characteristics of this camera system have been reported by Bixby (1981).

The camera is especially well suited to high-speed motion analysis when used with the copper vapor laser, as it can be used with an output designed to directly trigger this laser. The analog images stored on the magnetic tape were later digitized using a video frame grabber (Digital Graphics System CAT-100) to demonstrate that quantitative measurements can be obtained at these rates. The results are illustrated by Fig. 6 which shows one axial slice of the jet with only 166 μsec between successive frames. A 2 mm nozzle was used at a flow rate of 17.3 m/sec, corresponding to a Reynolds number of 2310. The region of observation is approximately 1.0 to 7.0 nozzle diameters downstream. Because the SP2000 camera system was available to us for only a short time, the data shown in Fig. 6 were not corrected for background and response.

Although this camera is the fastest of those considered here (up to 12 kHz), the dynamic range is the lowest (< 100). In addition, the degree to which the data must be corrected seems to be the highest. This is due, in part, to the parallel nature in which the data are stored. Since there are 32 different analog tracks that are recorded and must be played back in order to get a digital signal, the slight differences in the gain and offset of each of the 32 heads can give the image a streaked appearance.

## 7 Conclusions

Three different approaches have been demonstrated to digitally record the concentration of nozzle gas both temporally and in two dimensions. The first uses a slow-speed imaging system and a rotating mirror to obtain a high effective framing rate for a small number of frames. This technique can achieve the highest effective framing rates but is restricted to collecting a small sample of image data. It is well suited for use with double-pulsed laser systems and the dynamic range and low-light sensitivity achieved surpass those of the other systems discussed. The second technique, using a photodiode array camera, has the advantage of recording 320 consecutive digital images at a framing rate of 1.136 kHz. To achieve this rate, the pixel resolution is reduced to $128 \times 32$ pixels and the dynamic range is limited to $\sim 100$. The third method combines features of the first two but is not directly digital. Spatial resolution is exchanged for temporal resolution and continuous data acquisition is possible. While each of these approaches requires some compromise, the potential for obtaining quantitative data at rates fast enough to follow changes in turbulent flows is clearly demonstrated. This data should be valuable to further our understanding of these processes.

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## References

Becker, H. A. 1977: Mixing, concentration fluctuations and marker nephelometry. In: Studies in convection (ed. Launder, B. E.), Vol. 2, pp. 45–139. New York: Academic Press

Bixby, A. J. 1981: High-speed television camera and video tape recording system for motion analysis. Proc. Soc. Photo Opt. Instrum. Eng. 301, 58–65

Cattolica, R. J.; Vosen, S. R. 1984: Laser fluorescence imaging of combustion-torch ignition. 1984 Fall Meeting of the Western States Section of the Combustion Institute, Paper WSS/CI 84-58

Crow, S. C.; Champagne, F. H. 1971: Orderly structure in jet turbulence. J. Fluid Mech. 48, 547–591

Dyer, M. J.; Crosley, D. R. 1982: Two-dimensional imaging of OH laser-induced fluorescence in a flame. Opt. Lett. 7, 382–384

Dyer, M. J.; Crosley, D. R. 1984: A rapidly sequenced pair of two-dimensional images of OH laser-induced fluorescence in a flame. Opt. Lett. 9, 217–219

Escoda, M. C.; Long, M. B. 1983: Rayleigh scattering measurements of the gas concentration field in turbulent jets. AIAA J. 21, 81–84

Fourguette, D. C.; Long, M. B. 1983: Highly localized pressure perturbation induced by laser absorptive heating in the shear layer of a gas jet. Opt. Lett. 8, 605–607

Grove, E. R. 1982: Copper vapor lasers come of age. Laser Focus 18, 45–50

Kychakoff, G.; Howe, R. D.; Hanson, R. K. 1984: Quantitative flow visualization technique for measurements in combustion gases. Appl. Opt. 23, 704–712

Long, M. B.; Chu, B. T.; Chang, R. K. 1981: Instantaneous two-dimensional gas concentration measurements by light scattering. AIAA J. 19, 1151–1157

Long, M. B.; Fourguette, D. C.; Escoda, M. C.; Layne, C. B. 1983a: Instantaneous Ramanography of a turbulent diffusion flame. Opt. Lett. 8, 244–246

Long, M. B.; Tzeng, H.-M.; Fourguette, D. 1983b: Time-resolved two-dimensional concentration measurements in an acoustically driven flow. AIAA J. 21, 1085–1088

Merzkirch, W. 1974: Flow visualization, pp. 221–229. New York: Academic Press

Rosensweig, R. E.; Hottel, H. C.; Williams, G. C. 1961: Smoke-scattered light measurement of turbulent concentration fluctuations. Chem. Eng. Sci. 15, 111–129

Snow, J. B.; Zheng, J. B.; Chang, R. K. 1986: Increased sensitivity of a vidicon optical multichannel analyzer with a detachable electrostatic image intensifier. Appl. Opt. 25, 172–174

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