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An Imaging System for PLIF/Mie Measurements for a Combusting Flow

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ABSTRACT

The equipment required to establish an imaging system can be divided into four parts: i) the light source and beam-shaping optics, ii) camera and recording, iii) image acquisition and processing, and iv) computer and output systems. In this investigation, a pulsed, Nd:YAG-pumped, frequency-doubled dye laser which can freeze motion in the flowfield is used for an illumination source. A set of lenses is used to form the laser beam into a sheet. The induced fluorescence is collected by an UV-enhanced lens and passes through an UV-enhanced MCP intensifier which is optically coupled to a gated solid state CCD camera. The ouput of the camera is simultaneously displayed on a monitor and recorded on either a laser videodisc set or a Super VHS VCR. This videodisc set is controlled by a minicomputer via a connection to the RS-232C interface terminals. The imaging system is connected to the host computer by a bus repeater and can be multiplexed between four video input sources. Sample images from a planar shear layer experiment are presented to show the processing capability of the imaging system with the host computer.

1. INTRODUCTION

The application of laser techniques for flow visualization and measurement of the velocity field is fast becoming the norm rather than the exception in fluid dynamics research work. As such, it is not surprising that much effort is focused on the development of non-intrusive techniques that would provide more accurate description of the nature of the flow in different systems and under vastly different conditions. Most of the new optical and imaging techniques attempt to provide full-field information in time and in planar or volumetric space. Precisely this type of quantitative information would enable the researchers to investigate very complex flows of practical interest. Furthermore, often parallel to the experimental work, theoretical and computational developments are essential in constructing an accurate picture of the flow. However, these efforts have been severely limited by the problems in collecting a massive amount of data which is often needed to represent the flow. While most of the new laser diagnostic techniques provide an abundance of data, the means to precisely interpret the data are not clearly identified. Furthermore, in the case of volumetric measurements, one would face additional difficulties due to computer limitations that make it difficult to obtain statistical averages. Planar measurements on the other hand make it possible to obtain averages since it only uses a two-dimensional plane with time and eliminates the requirements of the third dimension.

The system described in this article is a Planar Reacting Shear Layer (PRSL). It is constructed in order to investigate the plane mixing layer with the ultimate goal of developing relationships between the existing computational fluid dynamics codes and the experimental results, the outcome of which would provide an understanding of fluid dynamics-combustion interaction. More specifically, the overall objectives are to obtain experimental data for validation of computational fluid dynamics codes; investigate the effect of flow acoustics on combustion processes and identify the mixing enhancement techniques. The details of the overall system which includes the PRSL test section is presented elsewhere.[1] [2] Here we have focused on the imaging component for PLIF and Mie scattering measurements in a combusting flow. Among some of the most recent activities in this area, one could cite the work of Ohba, et. al.[3] They used laser-induced fluorescence to make images for visualization and for quantitative measurements of the velocity field for the case of laminar water flow in different geometries. From their velocity profiles, they obtained the distribution of wall shear stress over the whole flowfield. The authors used a nitrogen pulsed laser for exciting the fluorescence particle. The laser pulses were five nanoseconds wide at 337.1 nm and 1 MW peak power. They used zinc sulfide particles of approximately 8 μm in mean diameter and 4.1 g/cc density for fluorescence particles. Ohba, et. al., photographed the motion of a time line representing a velocity profile along the laser beam and tracked it by a high speed video camera, 200 frames per second, positioned perpendicular to both the laser and the flow. An image intensifier was used to amplify the fluorescence light. In another study, Smith et.al., [4] visualized the instantaneous density field in compressible turbulent flows, at a Mach 2.9, using Rayleigh scattering in the ultraviolet. They discuss the advantages and restrictions of their technique for measuring the instantaneous density field in a plane by applying it to a zero pressure-gradient turbulent boundary layer developing on the nozzle wall, and in the unsteady three-dimensional shock wave boundary layer generated by a blunt fin. Their images were obtained by using an Nd:YAG laser that operated in the ultraviolet. They recorded cross-sectional images of the air density by direct Rayleigh scattering. Their laser operated at about 0.266 microns with a pulse duration of four nanoseconds, thereby freezing the cross-sectional image. The camera viewed the scattering at 90° and images are recorded at the laser pulse repetition rate of 10 Hz.

The appeal of the planar laser-induced fluorescence technique is largely due to its characteristics that allow one to identify different flow properties in a plane. Lozano, et.al.[5] have used this technique to measure the concentration of a passive molecular tracer in a turbulent axisymmetric nitrogen jet. They used a pulsed XeF excimer laser to form the light sheet. They recorded the emitted light by two low noise, high dynamic range CCD cameras. The images were analyzed statistically. They report their results for mean concentration, rms concentration fluctuations, scalar dissipation and cross-section centered means.

A new laser imaging diagnostic is reported by Dahm, et. al.[6] The technique is presented for achieving highly detailed, four-dimensional measurements of the full space and time varying conserved scalar field and the associated scalar energy dissipation rate field in a turbulent flow. The technique is based on high-speed, high-resolution, successive planar laser induced fluorescence imaging of a synchronized raster swept laser beam together with data acquisition using computer disk ranks. The measurement resolution is such that the resulting four-dimensional data are directly differentiable in all three space dimensions and in time.

2. SYSTEM DESIGN

Generally, imaging systems can be divided into four subsystems, namely: i) the light source and beam-shaping optics, ii) camera and recording, iii) image acquisition and processing, iv) and computer systems (Fig. 1). The optical system includes a laser unit with a series of collimators, mirrors, and spherical and cylindrical lenses to illuminate the flowfield. Usually, Mie scattering is not limited to a certain kind of laser system, but, laser induced fluorescence requires a high-power tunable UV laser such as an Nd:YAG-pumped, excimer-pumped, or flash-pumped pulsed dye laser or an excimer laser directly, depending on which species is present in the flow. The images gathered by the camera can either be recorded or directly stored on a image memory board. The use of a recording device depends on many factors, such as: the framing rate and the resolution of the camera, the image size of interest versus the size of the image memory boards, the image data transfer rate between the image memory boards and the host computer's disk storage. Finally, the image is acquired and processed by the imaging system. The processing can be real- or post- time based on specific applications. The host computer can be used to obtain more information from the raw images.

2.1 Optical System

In this design, the planar Mie scattering (PMS) technique is used to study the mixing process. The second harmonic (532nm) of a pulsed Nd:YAG laser is directed to the test cell by a series of collimators and mirrors and then focused into the flow by a lens system (Fig. 2). This lens system, which contains spherical and cylindrical lenses, forms the laser beam into a light sheet that traverses along the flowfield under study. The set of lenses is installed on a translation stage which is connected to a motion controller. This controller is remotely controlled by the host computer to move the laser sheet and the camera along the flow direction and allows the observation of different sections of the flowfield. The flow is seeded with titanium tetrachloride $TiCl_4$ which forms titanium dioxide TiO_2 particles. The resulting scattering is visualized at a right angle to the laser sheet onto a CCD camera. The high resolution camera has 754 x 488 pixels. The images so obtained can be related to the instantaneous physical phenomena of the flow.

For measurements of the instantaneous concentration and temperature field, the planar laser induced fluorescence PLIF technique is used. The beam from an Nd:YAG pumped, frequency-doubled pulsed dye laser is tuned to a wavelength corresponding to the desired excitation and fluorescence transitions. This laser beam is formed into a sheet by a series of lenses. Within the illumination plane, a fraction of the incident photons is absorbed and subsequently re-emitted with a modified spectral distribution. The induced fluorescence is imaged at right angle to the laser sheet onto a gated image-intensified CCD camera.

2.2 Camera And Recording System

The camera includes an UV-enhanced lens for signal intensification. Intensified lens technology using a micro channel plate MCP is well known and will not be discussed in detail here (Fig. 3). The pixel image that exits from the CCD output register is amplified and processed, adding vertical and horizontal timing pulses, to form a composite video signal.

The output of the camera can be recorded either on a component recording videodisc (CRVdisc) via a laser videodisc set which includes a laser videodisc processor and a recorder, or on a Super VHS tape via an editing video cassette recorder VCR. During the calibration process or testing of the facilities, the VCR is used to record the whole procedure. When an interesting phenomenon is observed, the images can be transferred from tape to videodisc using a time base corrector to give an exact synchronization. The videodisc recorder is used during an experimental run after everything else is calibrated and tested.

The laser videodisc set is capable of frame-by-frame video recording. It also has the capability to play back images at different speeds, 1/255 to 3 times normal speed, including freeze capability in both forward and reverse directions. The videodisc processor is equipped with three types of video signal input/output : namely, composite video signals, color diffference signals, and RGB signals. During the recording of experiments, the input signal is limited to the composite video signal from the camera. With this system, it becomes possible to record post-processed, pseudo-colored images from the imaging system in the form of RGB signals. Each CRVdisc can record 43500 images per side, which is equivalent to approximately 48 minutes recording time (30 frames per second). The videodisc set is controlled by a minicomputer with an imaging system via a RS-232C interface.

The S-VHS VCR is connected with a time code generator/reader to provide a capabilty of identifying each frame. The time code is recorded on the audio channel. Another VCR is used to record with a visible time code window appearing on each image to facilitate finding the frames of interesting events. Input and output signals are limited to composite video signals. Each tape provides about 120 minutes recording time. Presently, the VCR is not controlled by the computer, but it is expected to be modified to incorporate a controller via a RS-232C interface.

The video cassette provides longer continuous recording time while comparatively, the videodisc offers only one fifth of the time for one side (24 minutes vs. 120 minutes). The tape is rewritable and the disc is "write once, read many" (WORM). Both sets are controllable by the host computer via a RS-232C interface using a controller. On the other hand, the videodisc set provides an easy way to access any particular frame in a very short responding time while the VCR does not offer any easy way to forward or rewind to a certain frame. The videodisc has the capability to playback in variable speed including freeze motion with very clear images, but the VCR has no dynamic tracking device built-in and does not supply clear images in different playback speeds.

2.3 Image Acquisition And Processing System

The imaging system includes one analog system (AS) board, four digital image storage (DS) boards, and one pixel processor (PX) board plus the basic software (Fig. 4). Multiple synchronous video buses are used for image data transfers between the image acquisition, image storage, and image processing modules without loading the host computer bus. The AS board is capable, under software control, of multiplexing between four video input sources. For example, it is currently handling both the VCR and the videodisc sets. The AS includes multiple input and output look-up tables which can be used to compensate camera non-linearity or pseudo-color the image. The DS board allows data to be stored as 8-bit pixel values with 1-bit of state information or 16-bit values with 2 state bits which preserves accuracy when doing arithmetic oprations on 8-bit values. The state bits can be used to perform the graphic overlays which is useful in correlating the flowfield phenomena with the acoustic and LDV data. It can also be used to label each pixel for a conditional image processing on a pixel by pixel basis. The PX can be programmed to perform frame operations in real time. The software is installed on the host computer and the hardware is connected to the computer via a bus repeater.

2.4 Computer System

The computer system (Fig. 5) includes two CPU modules which share the synchronous memory interconnect (SMI) for access to the 8 MB system memory at 26 MB/sec. There is a separate Multibus for each CPU module. This bus communicates with the SMI and CPU at 6 MB/sec. It also supports graphic subsystem, multiple disk drives and tapes, terminals, and multiplexers. A 2 MB/sec STDplus Bus is connected to the Multibus through a data acquisition control processor (DACP). This bus supports the data acquisition modules which include a clock interface, a 1 MHz A/D converter and sample hold, and a 0.5 MHz D/A converter. An Ethernet controller is also connected to the Multibus which provides the capabilty of communicating with the Lewis supercomputer, mainframes, and graphics-enhanced workstations. The operating system is Real Time Unix (RTU) which includes both AT&T and Berkeley universe.

2.5 Integrated System

Figure 6 illustrates the interconnection among the different components of the imaging system. The host computer can be programmed to moniter and control most subsystems that were described previously. As such, this design enables the investigator to focus attention on the image output in real-time. At any given time, one can also access the hard copies of the constructed images for further analysis.

3. SAMPLE IMAGES

The experimental data were obtained using a planar shear layer (two dimensional). A sheet of laser light illuminated the mid-plane just downstream of the mixing knife edge (Fig. 7). A

Xybion CCD camera recorded the light intensity patterns every time the laser flashed (30 times per second). Titanium tetrachloride and steam were added to the upper duct which produced small TiO_2 particles that scattered the light.

An instantaneous mixing pattern is shown in figure 8. The figure illustrates the instantaneous spatial pattern as well as the radial profiles. It is clear that more definite structures are identified in the instantaneous image as opposed to what can be interpreted from the radial profile plots. It should be noticed that in this image the TiO_2 particles are not uniformly mixed at the upper duct exit.

The average contours of 512 images are shown in figure 9 as white bands superimposed on the instantaneous frame. One can view successive frames against the mean profiles which would be stationary and observe the fluctuations of the flow with respect to the fixed reference.

The standard deviation SD and SD radial contours are shown in figure 10. The magnitude of the SD is below 30 so the contours are not visible on this plot. When the magnitude of the SD is normalized by the local mean value, show in figure 11, the large relative deviations are evident in the shear layer. The profiles are expressed as the coefficient of variation CV.

The data presented is only a sample, showing the capability of the image recording system and its rapid handling of large quantities of data.

4. CONCLUSION

We have presented an imaging system design which includes a host computer, an image processing system, an image acquisition unit and data analyses and data reduction capabilities. At present, the system utilizes only one CCD monochrome video camera which is adequate for concentration measurements. However, two cameras and two wavelengths will be needed for temperature measurements. Perhaps the most important features of this imaging system can be summarized as follows:

1. A parallel system for image recording using both the video disc and video tape has been assembled which uses the advantages of both systems.
2. The video disc-video tape interface enables one to selectively choose single video images from the previously recorded tape and feed them into the disc for further analyses. This presents a capability for "controlled-data-reduction," where one scans through all the acquired images and selects only those sequences that contain the required information about the flow.
3. The system is designed such that "on-screen" one-on-one comparisons can be made between the computational fluid dynamics CFD results and the experimental images.

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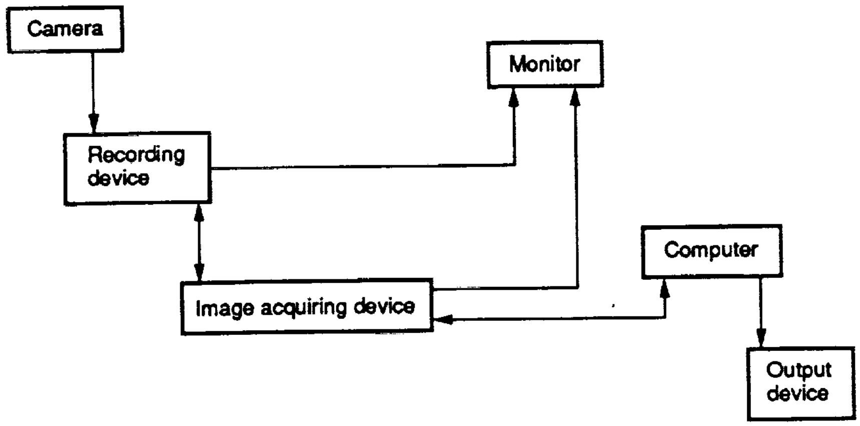

Figure 1.—Generalized imaging system.

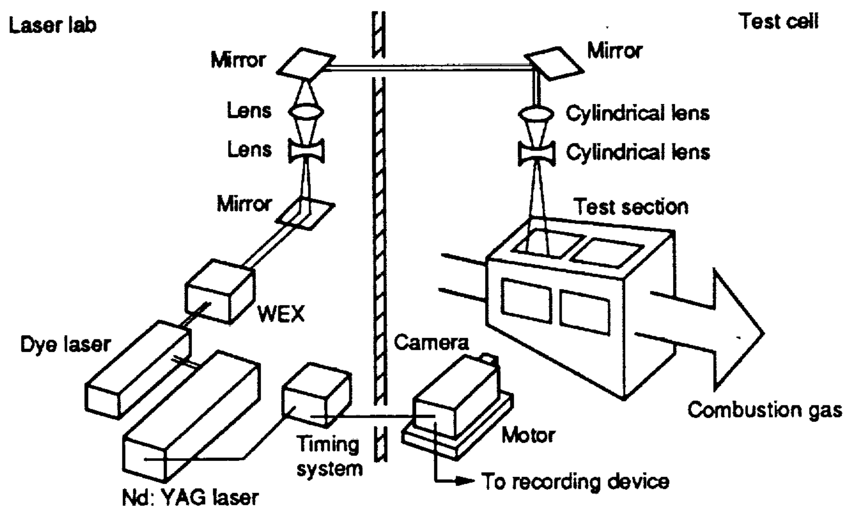

Figure 2.—Experimental apparatus.

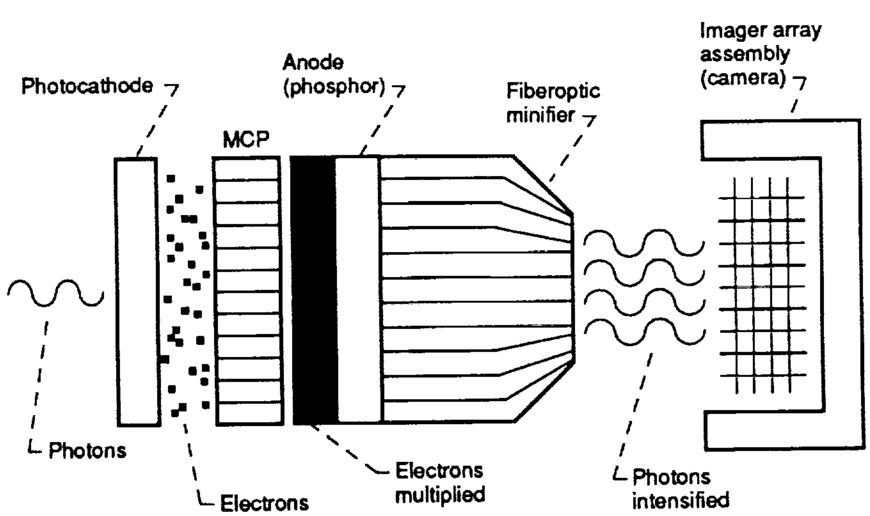

Figure 3.—Intensifier elements.

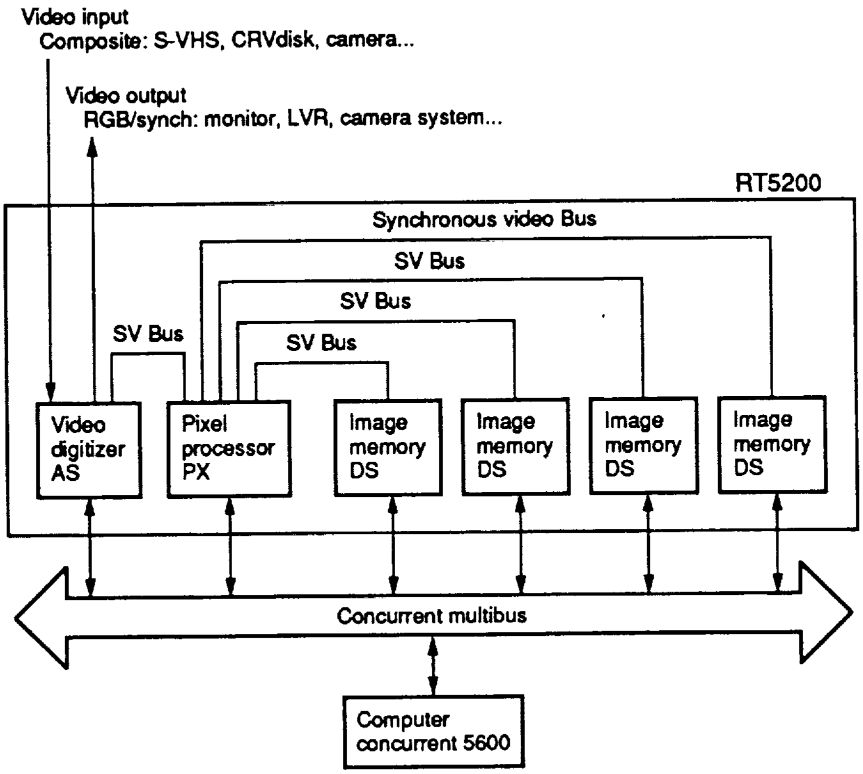

Figure 4.—Image subsystem (RT5200).

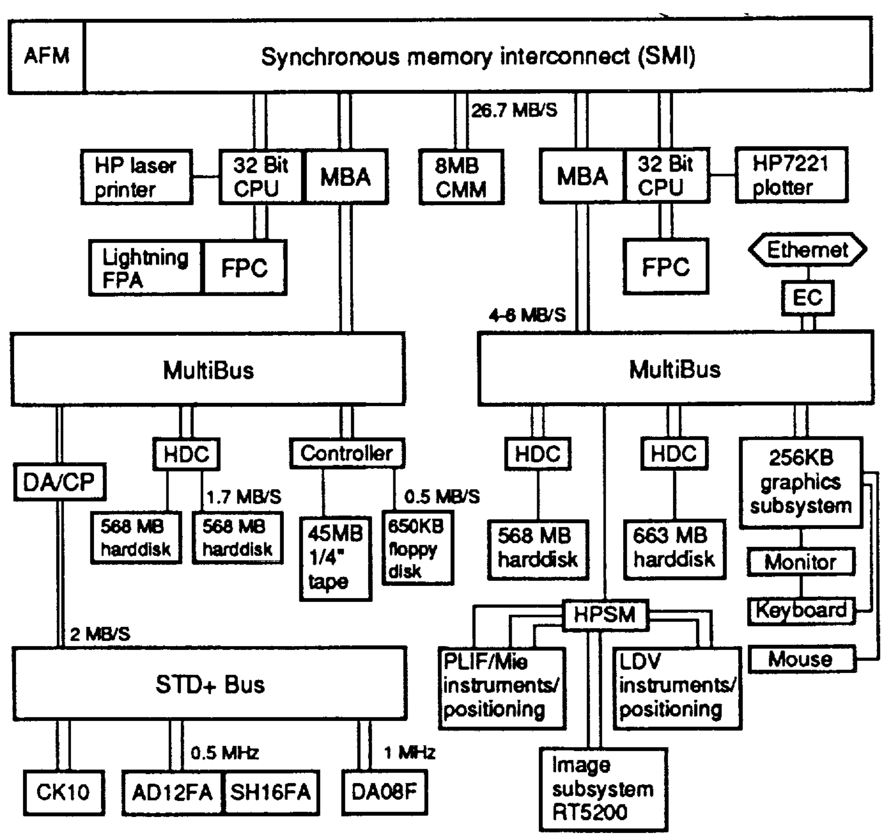

Figure 5.—Concurrent 5600.

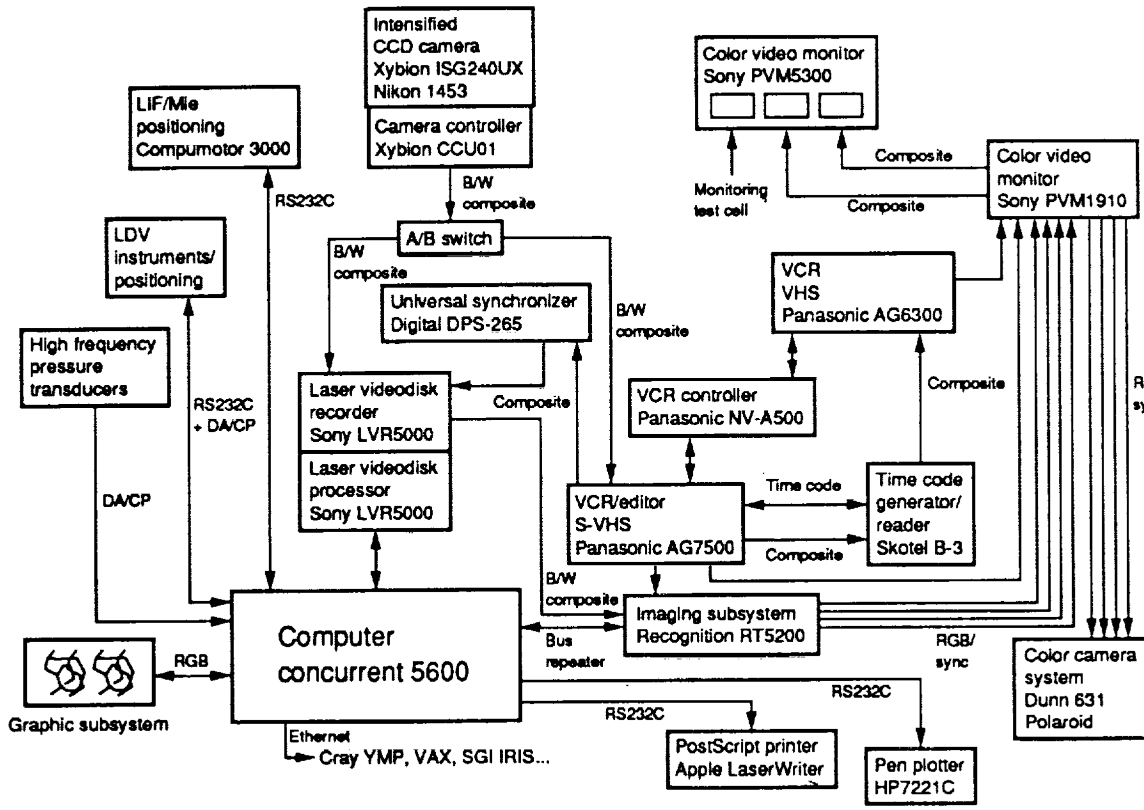

Figure 6.—System layout.

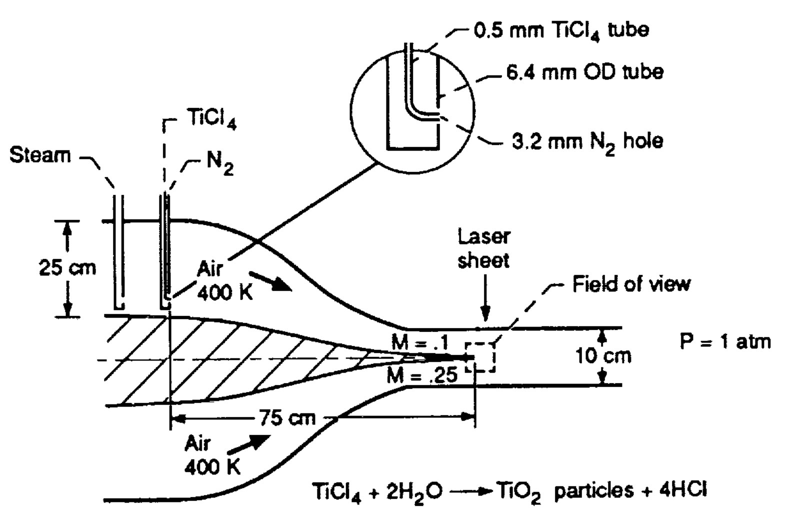

Figure 7.—Tracer injection into shear layer.

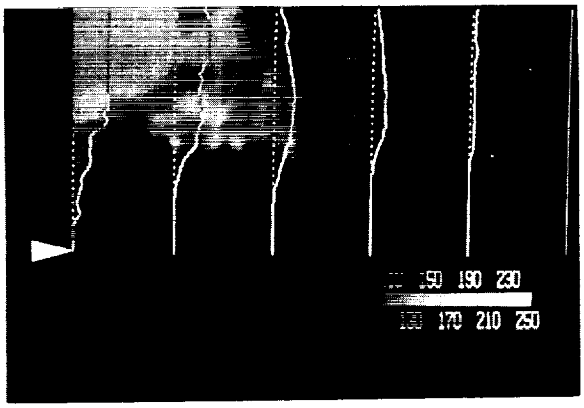

Figure 8.—Radial concentration profiles superimposed on instantaneous image.

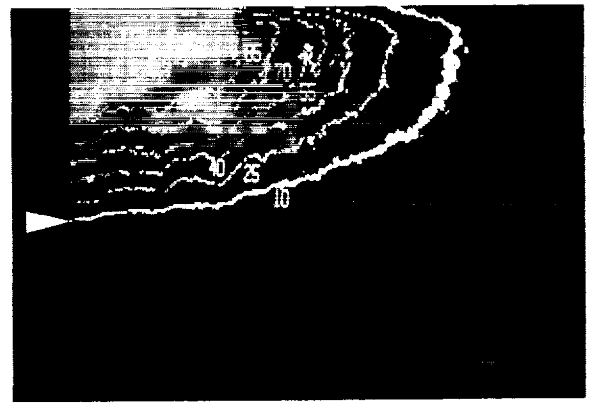

Figure 9.—Mean contours on instantaneous mixing.

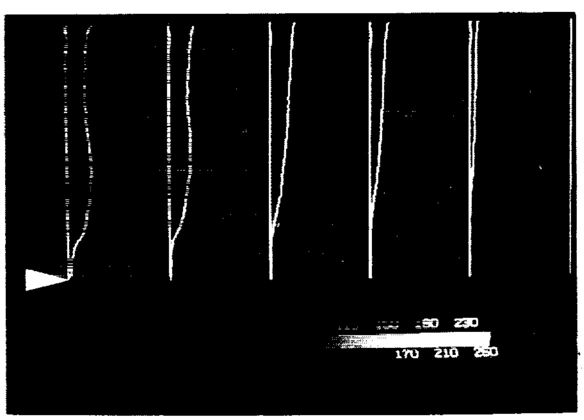

Figure 10.—Standard deviation (SD) profiles on SD field - 512 images.

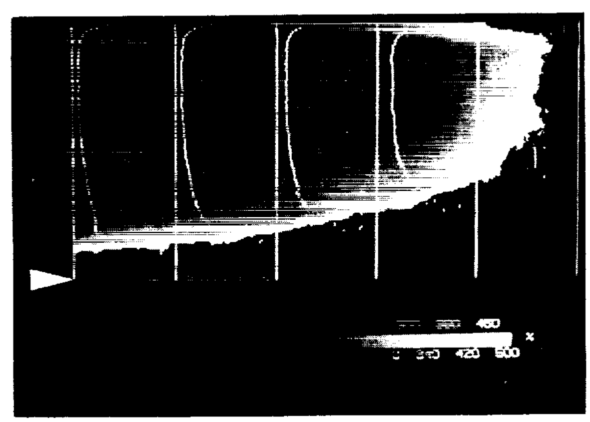

Figure 11.—Coefficient of variation (CV) profiles on CV field - 512 images.

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