A portable laser light-scattering probe for turbulent diffusion studies*

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A new instrument has been devised, based on light scattering principles, to measure real-time concentration variation in a turbulent flow. Used for turbulent diffusion measurements in a wind tunnel boundary layer, it can also be utilized for other turbulent mixing studies as well. The instantaneous concentration was detected by means of a 5 mW He–Ne gas laser as a light source, dioctyl phthalate aerosols as tracer particles, fiber optics as the scattered light transmitter, and a photomultiplier as a scattered light sensor. The instrument was designed to be moved to any location in a wind tunnel to measure steady or unsteady diffusion processes.

INTRODUCTION

In most experimental studies on turbulent mass transfer or diffusion, concentration samples are withdrawn from the sampling location and analyzed. The withdrawal rate is so designed that it is the same as the local mean convective velocity. This technique is referred to as the isokinetic sampling (IKS) method. The IKS method applies to the stationary situation where tracers are continuously introduced into a flow field. For an unsteady release, such as a sudden injection of tracer, the IKS method is not capable of detecting a rapid concentration variation because of the long time constant of the IKS probe. For instance, in a subsonic wind tunnel, the time required for a sample to reach the same mean value at the measuring point is about 5 sec.[1] Therefore, the average time constant of the detecting system is about 5 sec or longer. If a diffusing cloud takes 1 sec to pass a detection station, the prescribed IKS probe will fail to describe such a process. In addition, transient concentrations or concentration fluctuation quantities are often of interest. The IKS method apparently fails for the same reason—the long time constant. In this work, a light-scattering model has been designed for these unsteady diffusion measurements.

Among efforts to measure real-time concentration variation, light scattering is one of the most successful means. In an early study Rosensweig, Hottel, and Williams[2] used scattered light from artifically fed aerosols to measure transient concentration variations, with a dc driven chromatic light source as the incident light. The light was focused on a sample point in the flow, and the scattered light caused by the aerosol particles was detected by a lens–aperture arrangement set perpendicular to the axis of the incident light. This device was used to study a free air jet and turbulent flame. The over-all optical characteristics have been described by Becker, Hottel, and Williams.[3] The system was mounted in a fixed location; hence, it was suitable only for studying a mixing process within a movable transparent pipe. However, if an experimental site does not provide such ideal conditions, for instance, to study mass diffusion within a boundary layer in a wind tunnel, most of the bulky optical device cannot be used to carry out the measurements. (Most of the large wind tunnels do not have completely transparent walls; these problems also arise when using a Doppler velocimeter device).

Recently, Liu and Karaki[4] developed a portable light-scattering probe from two fiber optical bundles that transmit both incident and scattered light. At the ends of both fiber optic bundles, a set of lenses was added to focus the incident light and reduce the sample volume. The mobility of this probe was enhanced by the flexibility of the fiber optics; however, the incident light suffered from large transmission losses in the long fiber optic bundles. In addition, the chromatic light utilized as a light source made it difficult to define the scattered frequency. In the present work, a stable monochromatic laser light is used as an incident light source, and the coherence of the light ray is maintained by using a front-surfaced mirror as light deflector.

BASIC DESIGN PRINCIPLES

The assumptions of all classic light-scattering theories can be summarized as follows:

(1) The incident light is a plane, monochromatic, electromagnetic wave, such as that provided by a laser beam.

(2) The scattered light has the same frequency as the incident light wave, implying that the scattered frequency is

TABLE I. LLSP Components.

Name	Function	Remarks
	a. Incident light system	
Laser	Light source	5 mW, Spectral Physics model 120, 6328 Å, polarized, model 256 exciter
Reflecting mirror	Light deflector	12 mm diam.,0.15 mm thick front-surfaced
	b. Aerosol particles	
Dioctyle phthalate particles	Light scatterer	Atomization principle: air blast at mean diam $\sim 4\ \mu$
	c. Receiving system	
Optical aperture	Increase spatial resolution	Scattering angle $\theta \cong 12°$
Fiber optics	Scattered light transmitter	Transmission 4000–8000 Å, Dolan–Jenner Industries, BXL-36 3 ft long
Photomultiplier	Light sensor	RCA 7265, 14 stages: operating voltage: 2800 V dc S—20 response: 3000 to 8000 Å

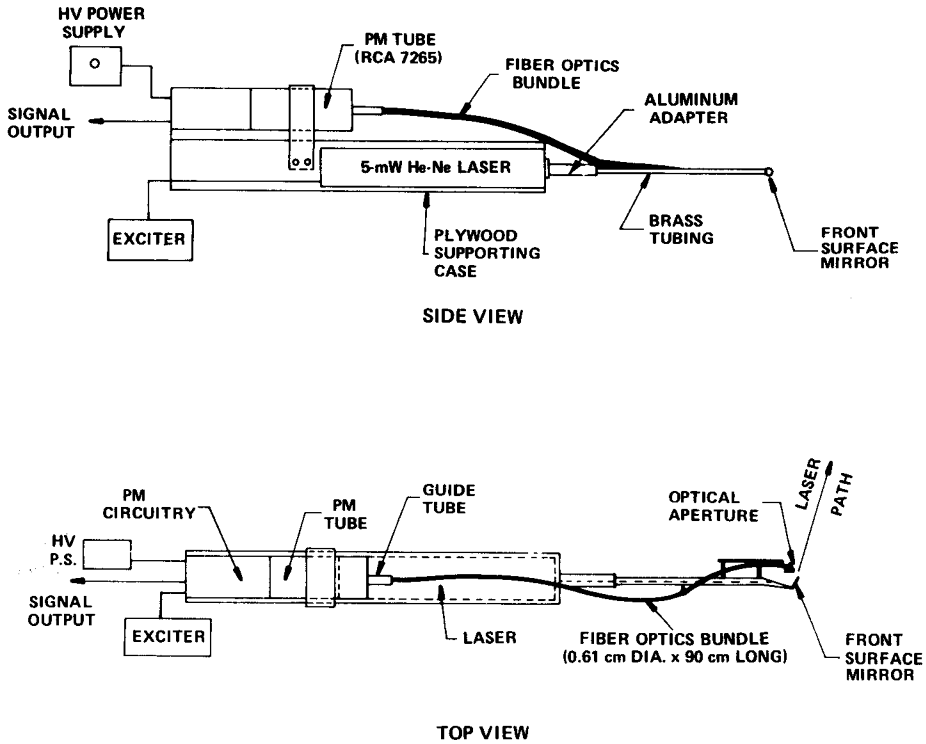


FIG. 1. LLSP schematic.

well-defined. This information is essential in selecting the scattered light transmission materials and the light-sensing instruments.

(3) When a light wave travels in a perfectly homogeneous medium, it will not be scattered.

(4) Scatterers are homogeneous spherical particles. Liquid droplets are usually spherical because of surface tension. For solid particles such as $TiCl_4$ or NH_4Cl aerosols, the scattering behavior is not readily defined.

(5) The total scattered light is the sum of the scattered light caused by each scatterer, i.e., independent scattering.[5] This implies that for low concentration measurements, a linear relationship exists between the total scattered light and the local concentration.

CONSTRUCTION AND COMPONENTS OF THE LASER LIGHT-SCATTERING PROBE

The present laser light-scattering probe (LLSP) was designed according to the prescribed light-scattering theories. Since the diameter of aerosols used ($\sim 4\,\mu$) is greater than the incident wavelength ($\sim 0.6\,\mu$), the scattering process falls into the Mie scattering category. To obtain an optimum signal-to-noise ratio, a forward scattering position was used. The selection of the fiber optics (as a scattered light transmitter) and the photomultiplier is based on knowledge of the incident light wavelength. The spectral response characteristics of each component of the LLSP will be given below (see Table I).

A schematic diagram of the probe is shown in Fig. 1. More details of the probe head can be seen in Figs. 2 and 3. A 5 mW He–Ne gas laser was installed in a $7.6\times10.2\times71.1$ cm plywood case. The probe head was mounted on the laser case with a 2.54 cm$\times$32 in.$^{-1}$ thread aluminum adapter. The supporting frame of the probe head was made of 1.27 cm o.d. and 0.63 cm o.d. brass tubes. The laser beam was deflected by a 1.2 cm diam, thin, front-surfaced mirror. An optical aperture was used to reduce the actual sample volume. The relative position of the deflected laser beam and the axis of the aperture was so chosen that the scattering angle was small but only a slight amount of incident light entered the aperture. Distortion of the flow caused by the presence of the probe was negligible since the sample volume was slightly ahead of both the mirror and the aperture. The scattered light that entered the aperture was thus transmitted through a 91 cm fiber optic bundle into the photocathode of the RCA-7265 photomultiplier, which was mounted on the plywood case where the laser was installed. Each component is discussed below.

a. Incident light source: 5 mW He–Ne laser

The important parameters of an incident light source in scattering studies are amplitude, polarization, coherence, and frequency. The amplitude is an indication of total power per unit area. Since the scattered light intensity is linearly proportional to the incident intensity, the higher the incident light intensity, the better the signal-to-noise ratio. However, the scattered light energy should not exceed the maximum yield of a light sensor. (For instance, the maximum yield of the photomultiplier used is 1 mA.) Polarization indicates the orientation of the electric field vector as a function of time in a plane perpendicular to the direction of propagation. In light-scattering theories, the maximum scattered light is located at the plane perpendicular to the direction of light propagation, and the aperture

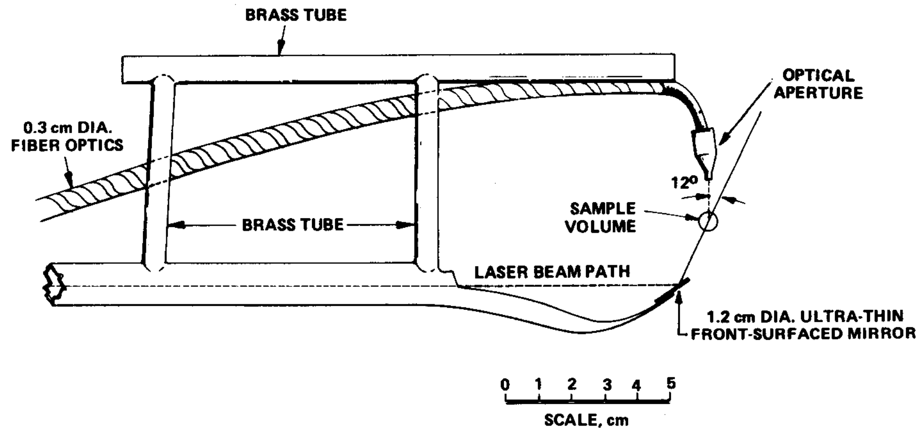


FIG. 2. Outline of LLSP head.

of this LLSP was located in this plane. Coherence confines the incident light energy within a small region. The single frequency, as mentioned before, makes the scattering process well defined.

b. Light reflector: the front-surfaced mirror

The purpose of this mirror was to reflect the laser beam to a desirable scattering angle without losing its coherence. The thickness of the mirror (0.15 mm) reduces possible aerodynamic distortion to a minimum.

c. Light scatterers: dioctyl phthalate aerosols

The aerosols used were the droplets of dioctyl phthalate (DOP), which were atomized by air-blasting the liquid surface. The generator, called a "collision atomizer," incorporates a baffle to remove most of the coarse aerosol particles. A description of the aerosol generator can be found in Ref. 5.

The aerosol size distribution was determined by an impingement method. The aerosol jet was placed against a clean glass plate for 5 sec, and those aerosols that remained

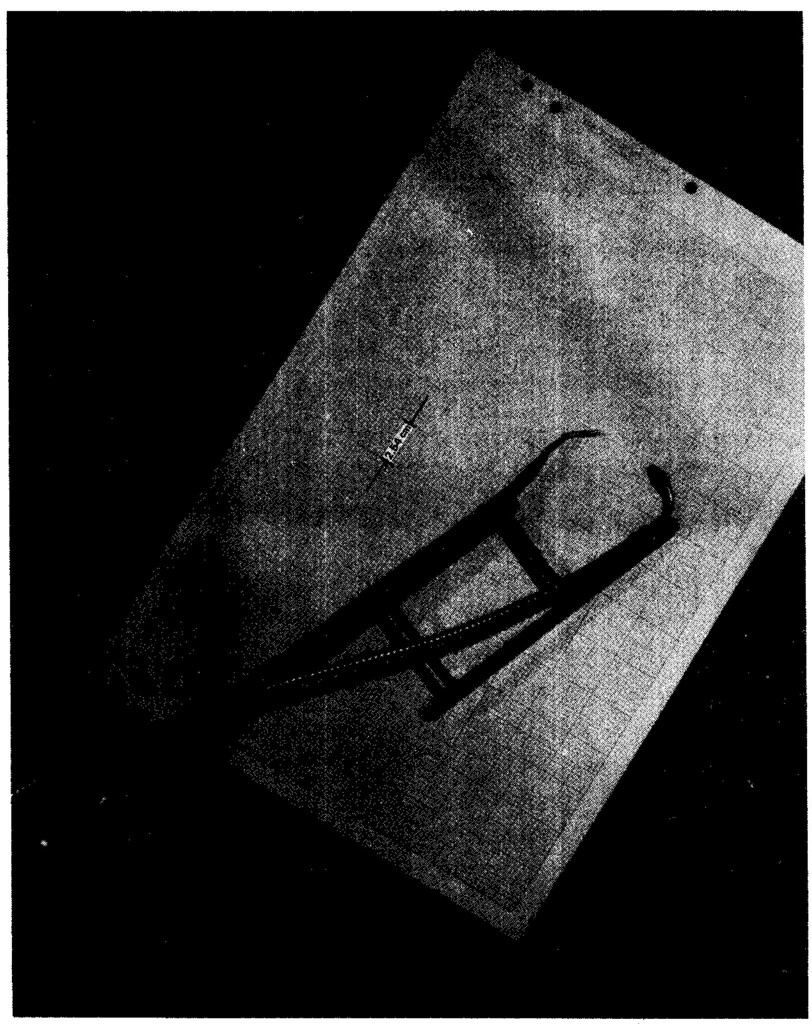


FIG. 3. Detailed photo of LLSP head.

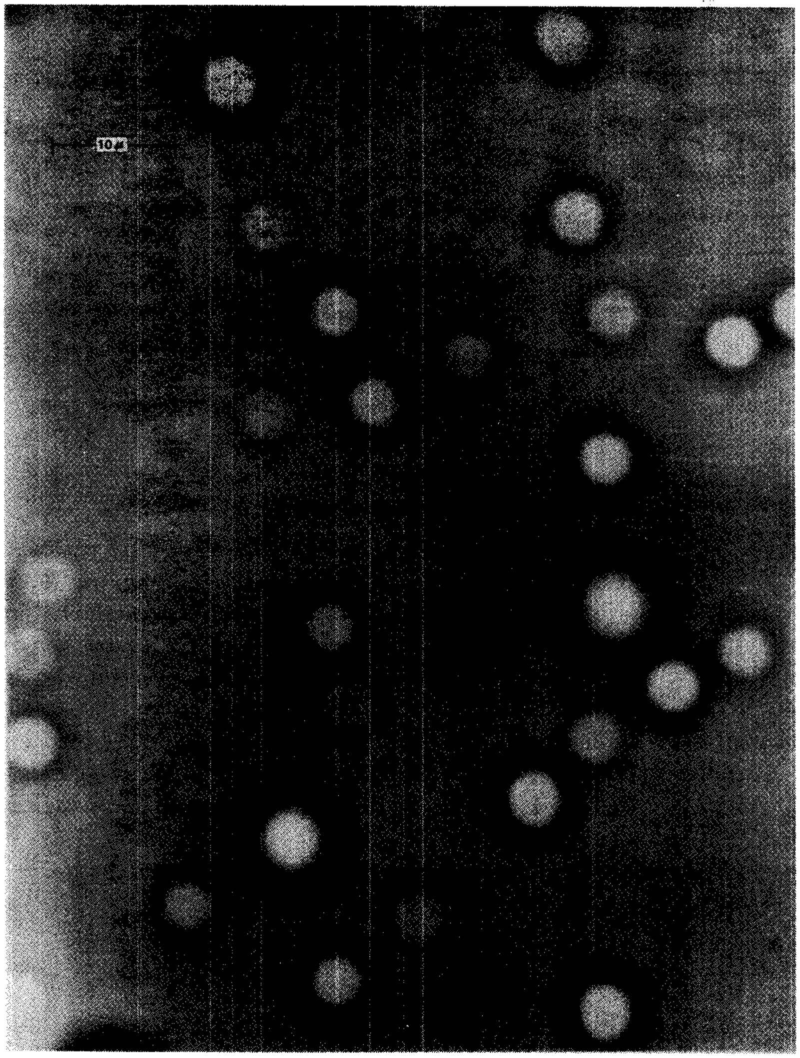


FIG. 4. Representative aerosol size distribution.

on the glass plate were examined under a photographic microscope. The representative size distribution, shown in Fig. 4, exhibits remarkable uniformity. A 10 μ microscale is used as a reference in Fig. 4. The mean aerosol size used for the following fall velocity calculation was 4 μ.

The mobility of aerosols in a turbulent flow is an important factor because it indicates how well an aerosol can follow the actual mixing process. In the LLSP, the over-all system frequency response also depends on the mobility of aerosols since the light-sensing system has a time constant at least less than 10^{-3} sec. With the consideration of the Cunningham correction factor,[6] the fall velocity V_f of aerosols in a still air is 7.18×10^{-2} cm/sec.[7] In a turbulent flow, the "mobility" is

$$\left(\frac{u'_{\text{aerosol}}}{u'_{\text{flow}}}\right)^2=\frac{1}{1+(2\pi f V_f/g)^2},$$

where g is gravitational acceleration, f is the frequency. If an aerosol particle can follow 90% of the rms amplitude of a sinusoidal motion or $u'_{\text{aerosol}}=0.9$, the frequency of the motion will be

$$f=\left(\sqrt{\frac{u'_{\text{flow}}}{u'_{\text{aerosol}}}}-1\right)\frac{g}{2\pi V_f}=1050\text{ cps},\quad \text{for}\ \frac{u'_{\text{flow}}}{u'_{\text{aerosol}}}=0.9.$$

Fortunately, most turbulent fluctuations fall within 1000 cps for subsonic flows. This mobility can be improved by trading off the output light intensities.

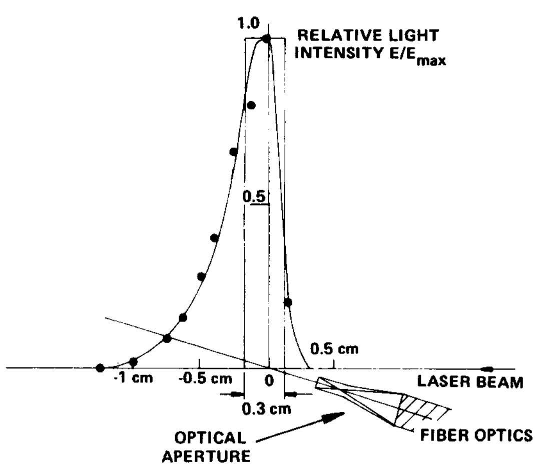


FIG. 5. Spatial resolution.

d. Aperture

An aperture was mounted at the end of the scattered-light receiving fiber optics to block the scattered light from un-

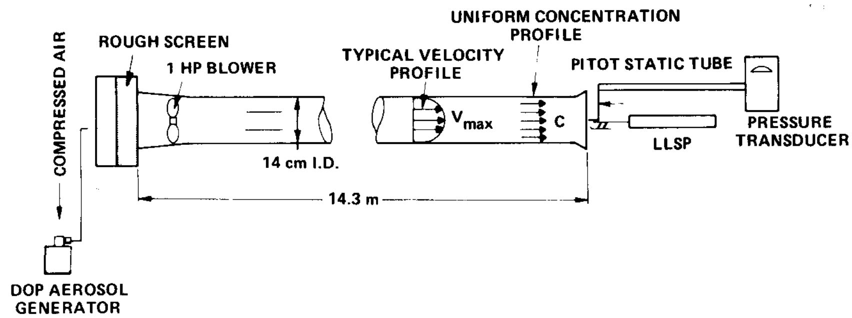


FIG. 6. Concentration calibration set-up.

desirable portions of the laser beam. The inside surface of the aperture was coated with a layer of optically black paint. (A lens combination may replace the aperture at the expense of increasing the total dead weight of the probe head and losing scattered light while the light rays pass through the lenses.) The spatial resolution was examined by injecting aerosols through a small nozzle (~0.07 cm i.d.) perpendicular to the laser beam. The results are shown in Fig. 5. The cross section of the laser beam was about 2 mm in diameter (from instruction manual). This sample volume is acceptable for "point concentration" measurements since most concentration spreads are at least three orders greater than the measured sample volume.

e. Scattered light transmitter: fiber optics

The advantages of using fiber optics as a light transmitter are flexibility and light weight. Of course, transmission loss should be considered when using fiber optics. The loss of light is proportional to the fiber optics length. The total transmission of the fiber optics used in the LLSP is about 50% (at 0.6 μ).

f. Scattered light sensor: RCA photomultiplier (PM) tube 7265

Like the fiber optics, the scattered light sensor was selected based on the principle of frequency matching. For optimum design, the spectral response characteristics of a light sensor must be considered when the incoming light frequency is defined. The scattered light wavelength, being the same as the incident wavelength, is 0.6 μ. The RCA tube 7265, with a photo-cathode spectral response of S-20 (extending from 0.3 μ to 0.8 μ), was chosen for the scattered light intensity measurement.

CALIBRATION AND IMPORTANT RESULTS

A. Calibration

The linearity of the PM tube output with respect to the input light energy was examined by systematically reducing the input light energy. This was done by inserting a set of precision optical filters (supplied by Optical Technology, Inc., Palo Alto, California). Since the transmission percentage against wavelengths for each optical filter was given, and the laser beam is a monochromatic source, the transmission could be evaluated. Of course, the PM tube will be "saturated" if one shoots the laser beam directly into the cathode. A double scattering from two pieces of photographic black paper was used to introduce the laser output into the PM tube as a constant light source. The incoming intensity was so adjusted that the PM tube current yield would not exceed 0.8 mA (maximum yield, 1.0 mA). The results indicated an excellent linear correlation.

The next important information is the relationship between aerosol concentration versus PM tube output. From the light-scattering theories, the scattered light should be linearly proportional to the aerosol concentration if the number concentration is not too large. We have already shown that the PM tube output is a linear function of incoming light energy. Let us now examine the independ-

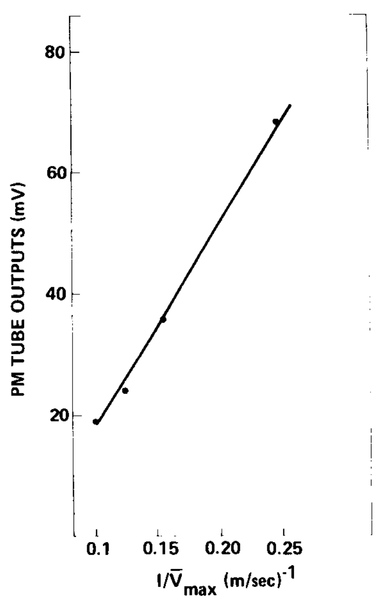


FIG. 7. Concentration calibration curve.

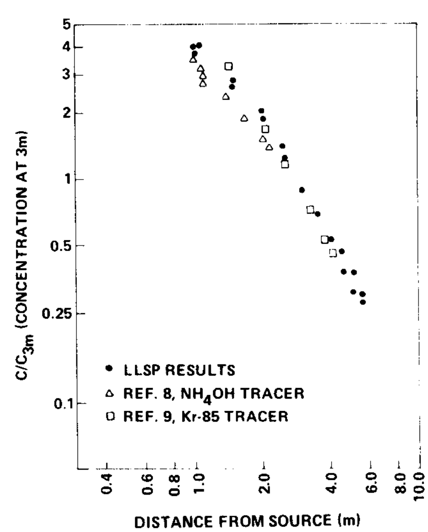
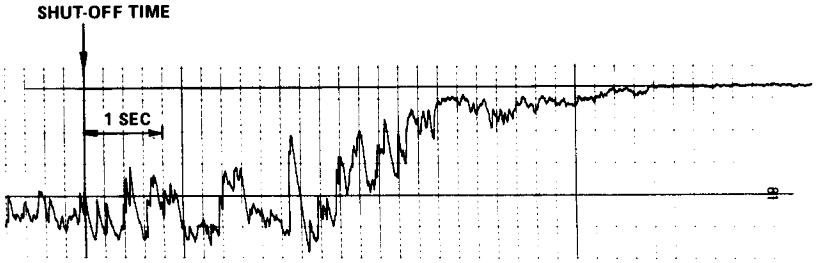


FIG. 8. Measurements of ground concentration distribution from a continuous ground point source by different methods.



NOTES: MEASURING DISTANCE: 3 METERS FROM THE SOURCE.
BAND PASS: 0-30 Hz (TIME t = 0 INDICATES THE SOURCE SHUT-OFF TIME)

FIG. 9. Concentration decay from short-time release plume.

ence of the scattering process. In other words, was the PM tube output linearly proportional to the aerosol number concentration?

This calibration process was carried out in a 14 cm i.d. cast-iron duct (whose length was 14 m, see Fig. 6). At the left end of the duct, aerosols were injected into the flow. A set of screens (grid sizes ≫ aerosol sizes) was used to encourage mixing. The calibration process was based on the conservation of mass since the rate of total injected aerosols is constant, thus

$$C_0 \propto 1 \Big/ \int_0^R r \cdot \bar{V}(r) dr \propto \frac{1}{V_{\max}},$$

where C_0 is the mean particle concentration and is independent of radius r because of complete mixing. $\bar{V}$ is the local mean velocity, and R is the i.r. of the calibration duct. $V_{\max}$ is the mean velocity at the center of the duct to monitor $V_{\max}$. As shown in Fig. 6, a Pitot-static tube was placed at the center of the duct. The LLSP was placed 2.5 cm below the Pitot-static tube. Figure 7 shows the plot results of $E-E_0$ vs. $1/V_{\max}$. E is the PM tube output and E_0 is the PM tube output from the background light. The results supported the excellent linear correlation between PM tube outputs and concentrations, and indicated that the process was within the range of independent scattering as long as the output signals were within the calibration range.

B. Experimental Validation

To compare the LLSP results with other mass transport results, the authors have chosen to duplicate an experimental condition, mass diffusion from a ground-released, continuous source in a fully developed turbulent boundary layer. Figure 8 displays the excellent agreement between the results of the present LLSP, the study by Malhotra and Cermak[8] with NH_4OH as tracer, and the work by Chaudhry and Meroney[9] with ^{85}Kr radioisotope gas as tracer.

A short-time release plume was also studied with the LLSP. The growth pattern of a plume after a step-function-like release and concentration decay after shut-off of a tracer source was examined. Figure 9 displays a typical output of concentration decay in a turbulent shear flow. Note that this unsteady behavior cannot be measured by IKS methods because of the long time constant mentioned previously. The results of the unsteady measurements are given in greater detail in Ref. 6.

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