CHAPTER 2

EXPERIMENTAL TECHNIQUES

2.1 Planar Mie Scattering

Planar Mie Scatter (PMS) is a commonly used method in flow visualization studies. It is most often used in experiments to qualitatively study the structural features of the flowfield (Chen and Driscoll, 1988; Clemens, et al., 1990; Goldstein and Smits, 1993). However, it can also be applied to the study of the mean concentration field and concentration fluctuations in turbulent flows. Studies by Rosenweig, Hottel, and Williams (1961) and Becker, Hottel, and Williams (1967) demonstrated the viability of making such measurements using PMS. Later studies, such as Yip, et al. (1987) show that this technique continues to yield useful results to the present.

2.1.1 Theory

For PMS experiments, seed particles are introduced into the fluid stream for which the distribution in the flowfield is desired. The flow is then illuminated with a sheet of light, and the resultant light scattering off the seed particles is passed into an imaging system for measurement of the scattered light intensity. In earlier studies, measurements were taken point-by-point using a photomultiplier tube (PMT). In modern experiments the heart of the imaging system is a scientific grade CCD camera, which allows the collection of data over an entire plane at one time. The measured light intensity at the PMT or each pixel in the CCD array is proportional to the concentration of seed particles in the volume imaged onto that pixel.

The energy flux scattered by a spherical particle is given by

\[ J_{\text{scat}} = \frac{1}{4} \pi D_p^2 \ d\omega_i \ d\omega_s \ \int \psi(\pi D_p / \lambda, \ \theta, n_p) \ J_{\text{inc}} \ d\lambda \]

where \( d\omega_i \) = the incident solid angle
\( d\omega_s \) = the detection solid angle
\( \theta \) = the angle from the incident beam to the detector
D\textsubscript{p} = the particle diameter
n\textsubscript{p} = the particle index of refraction
\frac{1}{4\pi}D\textsubscript{p}\frac{2}{\lambda}J\textsubscript{inc}d\lambda d\omega = the flux incident on the particle in a wavelength interval d\lambda
(Becker, Hottel, and Williams, 1967)

For large particles relative to the incident wavelength, the scatter function \psi tends to be independent of D\textsubscript{p} and \lambda. For particles which are small relative to the incident wavelength, the reduced, Rayleigh scattering equation can be used instead. However, the signal strength is much lower than for Mie scattering, resulting in the problems discussed earlier. Assuming no multiple scattering occurs, the flux scattered from a volume containing N like particles is N times the flux scattered from a single particle. Thus, this technique can be used to measure the concentration of scattering particles in a given measurement volume, which is indicative of the concentration of seeded fluid in that volume.

2.1.2 PMS System

A schematic of the system used in this study is shown in Fig. 2.1. Smoke was introduced into the nozzle fluid by the seeding system shown in Fig. 2.2. The smoke is generated by applying power to a coil of nichrome resistance wire in a container of mineral oil. The smoke is drawn out of the generator, through a mixing/damping chamber, and into the nozzle fluid stream by a venturi in the main jet air line. The amount of smoke introduced into the jet could be controlled by adjusting the variable power supply powering the heater. A large chamber surrounded the jet, and the laboratory exhaust system drew the seeded air out of this enclosure.

The flow was illuminated by an argon-ion laser operating single-line at 514.5 nm. The beam from the laser was focused across the measurement area by a crown glass, 1 m focal length spherical lens and formed into a horizontal sheet by a crown glass 13.7 mm focal length cylindrical lens. The sheet thickness was approximately 500 \mu m throughout the measurement area of 180 mm x 140 mm. The scattering from the smoke particles was directed to the detector using a plane mirror suspended in the enclosure. The mirror was placed well above the nozzle (approximately 100 nozzle diameters) in order to not interfere with the measurement area of the flow. The enclosure was shielded from room light in order to limit the background noise. Room lights were also turned off during the experiments to further limit the amount of spurious light reaching the detector.

The detector used was a gated, intensified CCD camera, a Stanford Computer Optics model 4 Quik 05 Q. The two-dimensional CCD array had 640x480 active pixel elements. The lens mounted to the camera was a Nikkor 50 mm, f 1.4, aberration-corrected lens. The camera was gated to 50 \mu s in order to effectively freeze the flow. In the highest speed flow studied, a fluid element would only move 850 \mu m, or about 1.5 degrees of phase with respect
to the excitation cycle during the exposure time. The image intensifier was charged to a gain of 750V to increase the signal levels, due to the short gate time used. The images were collected using a PC-486 with frame grabber and frame processor cards, Data Translation models DT 2851 and DT 2858, respectively.

In order to map the entire flow field, the nozzle was mounted on a vertical translation stage. The nozzle was then moved with respect to the laser sheet to capture images at varying z/D locations. The range available for translation of the jet extended to 210 mm below the laser sheet. Because the flows being studied were excited with a regular forcing function, by locking the imaging to a specific phase of the forcing function, phase-specific information could be gathered. By taking all the images in a data set at the same phase in the excitation cycle, the entire flow field could be mapped at a specific instant with respect to the excitation cycle. Sixteen images were averaged at each station to study the mean flow field. The data collection was automated, with the image collection PC also controlling the translation stage, using PC-LAB and DT-IRIS software routines from Data Translation. This program can be found in Appendix A, Section A.2.

2.2 Planar Laser-Induced Fluorescence

Planar Laser-Induced Fluorescence, or PLIF, is a very attractive method for use in measuring scalar fields in various flows. It has been used extensively in liquid flows (Dahm and Dimotakis, 1987; Yoda, 1992), reacting flows (Seitzman, et al., 1994; Hanson, Seitzman, and Paul, 1990; Vandsburger, et al., 1988), and non-reacting gaseous flows (van Cruyningen, Lozano, and Hanson, 1990; Grinstein and Gutmark, 1993). It is an attractive method because it is non-intrusive and can yield concentration data at all points in a plane through the flow. Because it uses a gaseous tracer with a density similar to that of the nozzle fluid, rather than a particulate, the probability that the concentration of the tracer in a given measurement volume reflects the actual concentration of the nozzle fluid in that volume is greater than with PMS.

2.2.1 Theory

In a PLIF experiment, a molecular tracer is excited by a light source within an absorption band of the molecule. The tracer can be one naturally occurring, such as PAH or OH in flames, or seeded into the flow, such as biacetyl or acetone in gaseous flows, or fluorescein dye in liquid flows. A portion of the tracer molecules absorbs the incident light and is raised to a higher energy state. These excited molecules may dissociate, return to the lower energy state via a nonradiative mechanism, such as quenching or intersystem crossing, or emit the excess energy in the form of photons (Hanson, Seitzman, and Paul, 1990). The emitted light can be collected onto a camera to acquire a 2-D map of the concentrations in the
illuminated plane. Because of the low intensity of the emitted light, the camera must have either an intensified or extremely low noise CCD array.

The number of photons emitted by the tracer per unit sheet area per unit time, $N_e''$, is given by

$$N_e''(x,y,t,\lambda) = \{\text{Photons incident per unit height}\} \cdot \{\text{Photons absorbed per unit length}\} \cdot \{\text{Photons emitted per photon absorbed}\} = \{N_i'(y,t) e^{-\alpha(\lambda) \int C(x,y)dx}\} \{\alpha(\lambda) C(x,y)\} \{\phi(\lambda)\}$$

where $N_i'(y) = \text{the number of photons per unit sheet height incident on the flow}$

$\alpha(\lambda) = \text{the absorption cross section of the tracer in cm}^2$

$C(x,y) = \text{the concentration of absorbing species in the lower energy level in cm}^{-3}$

$\phi(\lambda) = \text{the species 'quantum efficiency' for emission, or Sterm-Volmer factor, for this transition (Lozano, Yip, and Hanson, 1992)}$

For a pulsed laser, the total number of photons emitted is found by integrating with respect to time. Rayleigh scattering is neglected because the Rayleigh scattering cross-section is usually much less than the absorption cross-section. This equation assumes that saturation does not occur and that there is a single absorbing and emitting species.

The first term in the integral accounts for the attenuation of the beam by absorption of the incident radiation from prior fluid elements. This integral can be approximated, using a mean value $C_{avg}$ in place of $C(x,y)$, by

$$\alpha(\lambda) \int C(x,y)dx = \alpha(\lambda) C_{avg} x = x / l$$

where $l = 1 / (C_{avg} \alpha)$ is the optical depth of the seeded fluid. If $x << l$, the fluid is considered to be optically thin. In this case, light absorption by the fluid is negligible, and the exponential term can be approximated by 1.

Generally, the emission quantum efficiency, $\phi(\lambda)$, can depend on wavelength, flow temperature, pressure, fluid velocity, and gas composition. However, for polyatomic tracers, such as acetone, the fluorescence efficiency is largely independent of pressure and temperature (Lozano, Yip, and Hanson, 1992). It is also independent of the mixture composition for a large variety of gases. Then, if the absorbing medium in the flow is optically thin, the fluorescence intensity from a point in the flow is directly proportional to the concentration of the tracer $C(x,y)$. By collecting the fluorescence emission from a slice of a flow using a camera and laser sheet, a planar map of concentrations of marked fluid is obtained.
2.2.2 Tracer Selection

A number of gaseous tracers are available for use in PLIF experiments, depending on the data desired, i.e. concentration, temperature, pressure. Those used for concentration measurements include NO$_2$, NO, iodine, biacetyl, and acetone. NO$_2$ was proposed as a tracer for cold flow mixing in the seventies (Agarwal et al., 1976) but the technique was not extensively developed until much later (Gulati and Warren 1993). It is an attractive tracer because it is gaseous at room temperature, it can be excited in the visible by an argon-ion laser, the fluorescence is broad band and also in the visible, and it is stable and non-corrosive. The major drawback is that NO$_2$ is highly toxic, so great care must be taken in its use. NO has also been used as a tracer for cold flow in addition to its use in combustion diagnostics (Paul, Lee, and Hanson, 1989). It requires a UV excitation source, but the fluorescence is visible and NO is gaseous at room temperature. The major drawback again is the toxicity of the gas.

Iodine is also an attractive tracer for gaseous flows, as detailed by Hiller and Hanson (1990). It can also be excited by an argon-ion laser at 514.5 nm, and the fluorescence is in the visible (yellow). It is a solid at room temperature, but has a high vapor pressure, and is only mildly toxic. However, it is highly corrosive, so great care must be taken to protect the facility. In the presence of water, iodine forms ionic acid, so the carrier gas must be dry and the exhaust must be removed to prevent ionic acid from being inhaled by personnel in the laboratory.

Biacetyl has also been used as a PLIF tracer in gaseous flows (van Cruyningen et al., 1990, Lozano 1992). It is a liquid at room temperature but has a fairly high vapor pressure (30 torr at 20$^\circ$C) which allows it to be seeded in acceptable levels. It is also only mildly toxic. The absorption spectrum is broad band in the blue and near-UV, the fluorescence spectrum is broad band in the blue and green, and the phosphorescence spectrum is broad band in the green and yellow. The phosphorescence is quite intense, but it can only be used in slow experiments because of the long lifetime (1.5 ms), unless a gated camera is used. It is also strongly quenched by oxygen, so air cannot be used as the carrier gas. The fluorescence lifetime is short (15 ns) and is not quenched by oxygen. However, the intensity is much lower than that of the phosphorescence.

A detailed analysis of the suitability of acetone as a tracer for PLIF was carried out by Lozano, Yip, and Hanson (1992). They determined that the physical and photophysical characteristics of acetone make it a very good tracer for concentration measurements in gaseous flows.

Acetone, or dimethyl ketone, is a transparent liquid with a molecular weight of 58.08 and a specific gravity of 0.79. It is highly flammable, partly due to its high vapor pressure,
about 180 torr at 20°C. This high vapor pressure makes it possible to seed a gaseous flow with high concentrations of acetone (up to 30% mole fraction) by bubbling the nozzle fluid through liquid acetone. The toxicity of acetone is very mild and it is not considered carcinogenic (Lozano, Yip, and Hanson, 1992).

The absorption spectrum of acetone is broad band in the ultraviolet (225 - 320 nm, with a peak about 275 nm) and thus includes several wavelengths commonly available from excimer and YAG lasers. The emission spectrum is also broad band, but in the visible blue/green range (350 - 550 nm, with peaks at 435 nm and 480 nm), has an efficiency of $\phi = 0.2\%$, and a lifetime of less than 4 ns. The fluorescence signal is not dependent on either temperature or the composition of the surrounding gas. It was shown by Lozano (1992) that the fluorescence was linear with respect to acetone concentration and incident laser intensity for concentrations below 90 torr partial pressures (11.8% mole fraction), and incident laser energy below 1200 mJ/cm². The phosphorescence of acetone is greatly quenched by oxygen, thus for an air flow seeded with acetone, the phosphorescence will not interfere with the fluorescence signal.

2.2.3 PLIF System

Acetone was the tracer chosen for the PLIF experiments due to equipment considerations. Though the argon laser used for the PMS was available which could excite either iodine or NO₂, the facilities were not available to adequately seal the experiments, remove the dangerous gases from the exhaust, or protect the facilities from corrosion. An excimer laser was available which, using different gas fills, could lase at 248 nm (KrF), 308 nm (XeCl), 347 nm (N₂), 353 nm (XeF), or 435 nm (N₂+). Because of the large difference between the intensities available for acetone excitation (about 100 mJ/pulse) and biacetyl excitation (less than 1 mJ/pulse), and the much greater intensity of acetone fluorescence over that of biacetyl, acetone was selected as the tracer to be used.

A schematic of the PLIF system is shown in Fig. 2.3. A schematic of the seeding system is shown in Fig. 2.4. The acetone is seeded into the nozzle air by diverting part of the nozzle air through a chamber containing liquid acetone and mixing the seeded and unseeded nozzle air in a second chamber. The seeding level is controlled by varying the portion of nozzle air that flows through the acetone chamber. The seeding level was established at about 2% mole fraction, or 12 torr, to minimize the impact the seeding fluid would have on the nozzle fluid. Calculating the optical depth of air seeded with a 2% mole fraction of acetone yielded $l = 39.6$ cm. Since the only location which would have this concentration of nozzle fluid would be at the nozzle exit, and the largest nozzle exit used was 1.25 cm, the fluid was considered optically thin, and thus no corrections for absorption of the incident laser energy were necessary.
An excimer laser filled with XeCl as the lasing medium, emitting at 308 nm, was used as the UV excitation source. The pulse length was approximately 20 ns, and the trigger pulse was phase-locked to the excitation cycle. The laser had a response time of about 10 \(\mu s\) to a trigger pulse, which is less than one degree of phase shift with respect to the highest frequency excitation cycle used. The output of the laser was focused by using a fused silica 500 mm focal length cylindrical lens, and spread into a sheet using a fused silica 37.5 mm focal length cylindrical lens. The thickness of the laser sheet across the measurement area was about 500 \(\mu m\). The camera and enclosure were the same as those used for PMS. The 4 Quik 05 Q camera has a spectral range of 180 nm to 820 nm, which includes the excitation laser wavelength of 308 nm. Thus, any excitation light scattered in the system would also contribute to the signal measured, lowering the signal to noise ratio. However, because the Nikkor lens was made of crown glass rather than fused silica, the lens served as a long pass filter to exclude any elastically scattered ultraviolet light. No other filters were used on the collection optics in order to maximize the signal. The camera was triggered in advance of the laser with a gate width of 100 \(\mu s\). The camera gate width was chosen to keep the iris open until the end of the laser pulse while minimizing background light collection. The intensifier was charged to a gain of 850 V to maximize the fluorescence signal. The image collection and automation were identical to those in the PMS experiments.

### 2.3 Data Reduction

In order to extract valid intensity data from the images, which should be proportional to the tracer concentration, the images had to be corrected for the intensity variation across the laser sheet, background "noise", and any variations in the response of the CCD camera pixels. Correction for the variation of incident laser intensity due to absorption was not performed because the fluid under study was optically thin, as stated earlier.

First the acquired image was corrected for the variation in response of the CCD camera, pixel by pixel, using

\[
CF = \frac{(OF - DF)}{(FF - DF)}
\]

where CF is the corrected frame, OF is the data frame, FF is a flat frame, and DF is a dark frame (Photometrics, 1992). The flat frame image is taken of a uniformly illuminated flat field, to account for non-uniform pixel response. This was done by illuminating a flat, uniform white surface with incandescent light far from the surface and collecting an image of the surface with the camera. The dark frame image is taken with no illumination into the camera. This accounts for pixels which have an offset from zero. After these corrections, each pixel can be considered an independent linear photometer. The image was then rescaled so that the maximum intensity level after the correction matched the maximum intensity
before the correction. This correction process was also carried out on the background and normalization frames.

Once the correction for pixel variation was completed, all the images in the data set were corrected for the background and normalization frames, and then converted into an X, Y, Z, intensity format for plotting. The background frame was taken with the laser running, whether the argon or excimer, but the jet off. The normalization frame was taken with the laser running into a even field of tracer, again with the jet off. This was done by closing the exhaust system and filling the experimental enclosure with seeded air. An image was taken after the air and acetone in the enclosure were allowed to mix thoroughly. Because the laser sheet was not collimated, the entire plane had to be imaged rather than just a single line across the sheet to give a profile (van Cruyningen, Lozano, and Hanson, 1990). A background frame was subtracted from this normalization frame to give a corrected normalization frame. The data was binned into superpixels in order to increase the signal to noise ratio, and also to limit the number of data points in the set. The bin size chosen for plotting was 8 x 8 pixels, with the superpixel having the value of the average of the pixels inside. To determine the area in each pixel, an image of a grid with known spacing was taken, and the number of pixels between grid lines was measured, yielding the imaged area per pixel. For the 8 x 8 superpixel, the probe area was 2.25 mm x 2.8 mm. This was deemed to be sufficient resolution for this study because the focus was on bulk fluid mixing, with structures on the order of the jet diameter, rather than small scale mixing in the flows. This also matched the highest spatial resolution of the hot-wire measurements taken by C. Ding on the active triangular nozzle for three-dimensional analysis (1995). After binning, the data image was corrected, one superpixel at a time, using:

\[
CP = \frac{(DP - BP)}{NP}
\]

where CP is the corrected pixel, DP is the data pixel, BP is the background pixel, and NP is the normalization pixel. Each image was then scaled so that the maximum pixel value was 255 at that z location. After the correction, the pixels were output to a file in X, Y, Z, intensity ratio format, with this ratio ranging from 0 (zero intensity) to 1 (maximum intensity in the frame), for use in a plotting program. The program used for data conversion can be found in Appendix A, Section A.3.

Visualization of the data was performed on a PC-486 using the Tecplot 6.0 plotting program. This program was capable of generating two- and three-dimensional contour plots of the intensity data as well as extracting iso-intensity contours, or surfaces of constant intensity value, from the volume of data. The iso-intensity surfaces for a given value were found by linear interpolation between the data points in the set in those areas where the data did not match the given value. The intensity ratio value used to extract the iso-intensity contours was 0.5 for all cases. To show the cross-section of the jet under excitation, two-dimensional plots showing the contour of this intensity value were generated with planar
slices through the jet. Three-dimensional iso-surfaces for this intensity value were also generated to show the development of the jets in space under excitation.

The two- and three-dimensional iso-value contours in this study are plotted in the same manner as those presented by C. Ding (Ding, 1995). The data at each point in a particular z/D plane is normalized against the maximum value in that plane and the contour generated where the data value equals half of the maximum in the plane. Thus, the relative intensity at each point at a particular z/D location is indicative of the relative concentration of tracer at that location. These relative concentrations could not be normalized by the nozzle exit concentration to give absolute concentration levels because of difficulties maintaining a constant seeding level, varying output power from the excimer laser, and varying camera gain to increase the signal level at z/D locations far downstream.