Deposition and Dispersion of Inertial Aerosols in
Secondary and Turbulent Flow Structures

by

Kurt W. Roth

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Abstract

Aerosol deposition in secondary flows poses a challenging problem in several engineering applications. For example, particles in the wake of heat exchanger tube bundles or weld seams in fluidized bed combustors can severely erode the wall surfaces. This study examines the deposition of inertial aerosols (Sauter mean diameter greater than 40μm) behind a blunt plate mounted on a long splitter plate, i.e. a T-step configuration. Deposition rates are measured using a novel Laser-Induced Fluorescence (LIF) technique both in the recirculation region immediately behind the T-step (secondary flow) and the approximately plane mixing layer following flow reattachment. The parameters of step height, mean flow velocity, and particle diameter are varied to obtain deposition rates for over two orders of magnitude in Stokes Number.

Aerosol deposition in the recirculation zone is strongly depressed relative to the post-recirculation mixing layer region and a flat plate turbulent boundary layer. Particle number density profile measurements indicate that the low secondary flow deposition rates occur because the particles possess too much inertia to successfully negotiate the streamline curvature at the T-step and become entrained in the secondary flow. In addition, aerosol deposition rates do not appear to scale well with the secondary flow eddy-turnover timescale, i.e. with $x_r/U$.

Deposition in the post-reattachment approximate plane mixing layer scales quite well with the local fluctuating velocity normal to the wall, i.e $v'$. The plane mixing layer deposition rates also appear to lie below those found in a turbulent boundary layer; however, when the local number density is taken into account, the deposition rates then agree with the turbulent boundary layer deposition rates. This implies that secondary flow deposition rates cannot be estimated by knowledge of but global flow qualities; the flow and its effect upon the dispersion and resulting aerosol distribution must also be understood. Gravity appears to have a negligible effect upon the deposition rate in all the cases examined.

LIF deposition measurements in a turbulent boundary layer agree well with past measurements and establish the validity of the LIF technique.

Velocity response experiments performed in the decaying turbulence field behind a biplane grid displayed qualitative evidence of the “convective crossing trajectories effect”. That is, the particle velocity response exceeded that of the local flow field due to the mean
flow convecting the inertial particles from a region of higher turbulent intensity to lower intensity while the decay of the particle turbulent intensity lagged that of the flow field.

Additional efforts revealed that the Aerometrics’ Phase Doppler Particle Analyzer (PDPA) has a “background” rms velocity of about 1.5%, and that this error is highly dependent upon particle diameter and photomultiplier voltage.

Thesis Supervisor: John H. Lienhard V
Title: Associate Professor of Mechanical Engineering
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I became interested in engineering at Mount Hebron High School, where Dave Oppelt taught me physics my junior and senior years. “Doc Op’s” unique teaching style, a fusion of enthusiasm and didactic labs, aroused my interest in mechanics and convinced me to attend M.I.T. At M.I.T., I decided to pursue fluid mechanics after taking 2.20 taught by Prof. Probstein. During my junior year, I participated in my first UROP with Prof. Patera. The following summer, I became immersed in fluid mechanics research working with Prof. Leehey in the Acoustics & Vibration Lab wind tunnel. His patience, willingness to challenge me and his collegial modus operandi made research a joy and Prof. Leehey the ideal mentor. It is primarily due to his generosity that I decided to pursue graduate work in fluid mechanics. Graduate student Kay Herbert helped to make this a special experience.

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## Nomenclature

<table>
<thead>
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<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Constant in expression describing the decay of grid turbulence; a constant for the reflection of gas molecules from a particle</td>
</tr>
<tr>
<td>b</td>
<td>Coefficient in particle drag expression when r~l</td>
</tr>
<tr>
<td>c_d</td>
<td>Concentration of fluorescein salt dye</td>
</tr>
<tr>
<td>D</td>
<td>Spinning disc diameter</td>
</tr>
<tr>
<td>D_j</td>
<td>Diameter of VOAG jet</td>
</tr>
<tr>
<td>D_h</td>
<td>Channel hydraulic diameter</td>
</tr>
<tr>
<td>d_b</td>
<td>Diameter of laser beam</td>
</tr>
<tr>
<td>d_p</td>
<td>Particle diameter</td>
</tr>
<tr>
<td>d_straw</td>
<td>Straw diameter used in straw bundle</td>
</tr>
<tr>
<td>d_10</td>
<td>Number mean particle diameter</td>
</tr>
<tr>
<td>d_20</td>
<td>Area mean particle diameter</td>
</tr>
<tr>
<td>d_30</td>
<td>Volume mean particle diameter</td>
</tr>
<tr>
<td>d_32</td>
<td>Sauter mean particle diameter</td>
</tr>
<tr>
<td>E</td>
<td>Molar absorptivity of fluorescein dye</td>
</tr>
<tr>
<td>F_m</td>
<td>Particle drag</td>
</tr>
<tr>
<td>f_b</td>
<td>Natural frequency of jet breakup</td>
</tr>
<tr>
<td>f_d</td>
<td>Driving frequency of jet</td>
</tr>
<tr>
<td>h</td>
<td>Test section height</td>
</tr>
<tr>
<td>h_p</td>
<td>Protrusion height</td>
</tr>
<tr>
<td>h_s</td>
<td>Step height</td>
</tr>
<tr>
<td>I</td>
<td>Light Intensity</td>
</tr>
<tr>
<td>I_f</td>
<td>Light absorbed by fluorescein</td>
</tr>
<tr>
<td>I_0</td>
<td>Laser Intensity</td>
</tr>
<tr>
<td>j</td>
<td>Deposition rate</td>
</tr>
<tr>
<td>K</td>
<td>Film thickness equation coefficient</td>
</tr>
<tr>
<td>K_D</td>
<td>Deposition Velocity</td>
</tr>
<tr>
<td>l</td>
<td>Mean free path of carrier fluid</td>
</tr>
<tr>
<td>l_i</td>
<td>Stop distance of aerosol</td>
</tr>
<tr>
<td>M</td>
<td>Biplane grid mesh size</td>
</tr>
<tr>
<td>N</td>
<td>Number count of aerosols in a distribution</td>
</tr>
<tr>
<td>N_D</td>
<td>Number density of aerosols</td>
</tr>
<tr>
<td>n</td>
<td>Exponent describing the decay of grid turbulence; Spinning disk rotation rate</td>
</tr>
<tr>
<td>n_f</td>
<td>Number of fringes</td>
</tr>
<tr>
<td>Q</td>
<td>Volume feed rate to spinning disk; constant in expression for particle drag when r~l</td>
</tr>
<tr>
<td>P</td>
<td>Fluorescein film thickness calibration constant</td>
</tr>
</tbody>
</table>
\( Q_f \) Volume rate of aerosol production
\( r \) Aerosol radius; spinning disk radius
\( \bar{r} \) Mean aerosol radius
\( t \) Deposition film thickness
\( r \) Mean aerosol radius
\( t \) Deposition film thickness
\( t_{tr} \) Deposition run time
\( U \) Mean flow velocity
\( u_t \) Friction velocity
\( u' \) Flow Root Mean-Squared (RMS) velocity
\( V \) Deposition velocity
\( V_+ \) Deposition velocity in viscous units
\( V_j \) Jet velocity of VOAG.
\( V_p \) Particle instantaneous velocity
\( v_d \) Deposition velocity
\( v' \) Particle RMS velocity; fluid RMS velocity normal to a surface
\( w \) Tunnel width
\( w' \) Transverse fluctuating velocity component
\( X_f \) PDPA fringe spacing
\( x \) Streamwise coordinate
\( x_r \) Mean reattachment length
\( x_0 \) Virtual origin of homogeneous flow field
\( y \) Vertical coordinate normal to a horizontal surface
\( y_+ \) Distance from a wall in viscous units
\( y_s \) Splitter plate thickness
\( y_t \) Half-tunnel height (= \((h - y_s)/2\))
\( z \) Longitudinal coordinate
\( Re_c \) Reynolds Number based on channel hydraulic diameter
\( Re_p \) Reynolds Number based on particle diameter
\( Re_s \) Reynolds Number based on step height
\( Stk \) Stokes Number
\( \alpha \) Logarithm of the root-mean squared variation of particle diameter
\( \beta \) Vorticity of secondary flow
\( \Gamma \) Boundary layer thickness; channel flow half-height
\( \delta \) Boundary layer thickness; channel flow half-height
\( \delta f \) Deposited film thickness
\( \delta t \) Fringe crossing time interval
\( \theta \) Angle of PDPA configuration
\( \varepsilon \) Turbulent dissipation rate
\( \Lambda_g \) Integral scale of turbulence
\( \lambda \) Wavelength of jet disturbance; laser emission wavelength
\( \lambda_{opt} \) Optimum Wavelength of jet disturbance
\( \mu \) Viscosity of air
\( \mu_f \) Viscosity of aerosol fluid
\( \nu \) Kinematic viscosity of air; Poisson’s ratio
\( \rho \) Density of air
\( \rho_p \) Density of aerosol
\( \sigma \) Surface tension of fluid
\( \sigma \) RMS velocity fluctuation measured by PDPA
\( \sigma_g \) Degree of spray monodispersity for a log-normal distribution
\( \sigma_m \) RMS velocity fluctuation due to long-term \( \bar{U} \) drift
\( \sigma_p \) RMS PDPA velocity error
\( \sigma_r \) Radial stress
\( \sigma_Y \) Yield strength of material
\( \tau \) Particle relaxation time
\( \tau_f \) Characteristic flow time scale
\( \tau_k \) Kolmogorov time scale
\( \tau_M \) Characteristic time scale of integral length scale
\( \tau_p \) Particle time scale and particle relaxation time
\( \tau_+ \) Dimensionless particle relaxation time
\( \tau_r \) Reattachment Time Scale
\( \omega \) Rotation rate of spinning disk
Chapter 1 INTRODUCTION

Enhanced deposition rates occur in a secondary flow when an entrained particle strays from the flow streamline and impacts a surface. A particle with little inertia tends to follow the flow exactly and must rely upon non-impaction mechanisms (i.e. diffusional, thermophoretic, and gravitational settling) to deposit because the flow structure does not intercept the wall. On the other hand, more inertial particles will stray further from flow structures because they react more slowly to the flow. Moderately inertial aerosols, aerosols that exhibit some slip between the particle and the flow, behave in a regime between the two and deposition rates would appear to be governed by how accurately the particles trace the flow, or in other words, how precisely the velocity response of the aerosol mimics that of the flow. Experimental measurements of deposition rate behind a flow obstruction (Kim et al., 1984) indicate that deposition rates can be greatly augmented by a secondary flow structure, while measurements of particle dispersion behind a backward-facing step (Ruck and Mikiola, 1988) suggest that heightened deposition results from the particles entering the secondary flow, deviating from the eddy and impacting the wall. In spite of the much higher deposition rates reported in secondary flows, aerosol interaction with secondary flow structures has not received much attention. The primary goal of this thesis is to experimentally elucidate the deposition behavior of moderately inertial aerosols in secondary flows.
1.1 The Contexts of Aerosol Deposition

The dispersion and deposition of aerosols occurs in numerous engineering applications related to the secondary flow described above. Aerosols have been implicated in the erosion of metal surfaces (Smeltzer et al., 1969) and thrust nozzles (Bailey et al., 1961). Tabakoff et al. (1991) discuss how the dust, salt and sand particles inhaled by gas turbine engines impact upon the turbine blades and wreak havoc upon the performance, endurance and reliability of the turbines. Aerosols in coal combustors accumulate on the surfaces of heat exchanger tube bundles, fouling the surface and degrading heat exchanger efficiency (Zhang et al., 1992).

Fine coal particles can dramatically erode surfaces of fluidized bed coal combustors. Many investigators note that erosion is particularly extreme in regions where the particle-laden flow passes over an object in the flow, such as a heat exchanger rod, welding seam, discontinuity in a wall, etc. (Johnk and Wietzke 1989, Bixler 1989, Miller 1989, Elsner and Friedman 1989). In each instance, augmented erosion coincides with the existence of a secondary flow: the alternating vortices shed off a heat exchanger rod or the separating-reattaching flow fore and/or aft of a step such as a weld seam. Humphrey (1990,1993) has provided comprehensive reviews of the role of impacting particles in surface erosion.

The transport and subsequent deposition of toxic and carcinogenic particulates in the lung is a related problem area. Pollutants such as cigarette smoke are inhaled and deposit in the tracheobronchial tract; the spatial distribution of deposition within the lungs of particles of a given size is of primary interest in assessing the toxic potential of specific pollutants. If the regions of highest deposition rate can be identified, therapeutic aerosols could be targeted to the high-risk regions. Towards this end, deposition studies in human lung casts (Schlesinger et. al. 1977) have been performed. They conclusively demonstrate
that deposition rates of particles between approximately 0.1 and 3μm near lung bifurcations (branchings) are much greater than in the straight passages. Earlier studies (Auerbach et al. 1961) found that the highest incidence of primary lung carcinomas are near the bifurcations, and it is generally believed that increased particle deposition in specific areas of the lung caused some types of cancer. To explain such findings in terms of the fluid flow within the lungs, Schlesinger et al. attributed the increase in deposition rate to the impact of inertial aerosols that fail to navigate the streamwise curvature present at bifurcations.

Experimental simulation of a lung bifurcation by Jan et al. (1989) highlighted the vigorous secondary flows occurring at a bifurcation. Similarly, Kim (1984) measured the deposition rate of moderately inertial aerosols behind an obstruction in a pipe flow - representative of a partially obstructed lung bronchus - and discovered that deposition in the reattachment zone was almost one hundred times that in unobstructed flow. He cited the presence of the strong secondary flow behind the step as the reason for the augmented deposition rate. Secondary flows are also usually present in curved tubes, such as bronchial airways and pipe elbows.

Ultra-fine aerosol deposition (dp = 0.01 - 0.5 μm, say) studies provide further evidence of elevated higher deposition rates in secondary flows. Studies at lung bifurcations performed with ultra-fine aerosols found that deposition rates were more than twice as great at those predicted by a unidirectional-flow diffusional theory (Cohen and Asgharian (1990), Cohen et al. (1990)). Feng (1993), however, evaluated ultra-fine aerosol deposition at various positions behind a forward-backward facing step using a novel transmission electron microscopy (TEM) technique, finding lower deposition rates in the region of secondary flow.
1.2 Overview of Aerosol Dispersion

The fundamental issue of how closely a particle of a given inertia follows a flow having a characteristic timescale $\tau_p$, in addition to strongly influencing aerosol deposition rates in turbulent (e.g. Maxey, 1987 and Hjelmfelt and Mocros, 1966) and secondary flows, also bears upon the validity of Laser Doppler Anemometry (LDA) or Particle Image Velocimetry (PIV). To apply LDA, the flow is seeded with particles and the LDA apparatus measures the velocity of the particles; it is assumed that the particles accurately represent the behavior of the flow and move approximately at the velocity of the flow. In reality, particle behavior may not accurately portray the fluctuating velocity of the fluid, since the inertia of a particle may prevent it from following all scales of the flow. A particle that would allow accurate measurement of the velocity field using LDA would have at least three characteristics. First, the particle would be much smaller than the length scale of an eddy, so that the particle itself would not create a turbulent flow field. Second, the particle must have a timescale $\tau$ that is much less than the smallest time-scale of the flow to insure that the particle, despite its inertia, will be able to trace the smallest swirling motions of the flow. Third, the mass loadings of the particles would be small enough so that it did not damp the flow field turbulence (Hestroni, 1989) or alter the momentum of the flow field.

1.3 The Essential Problem

This thesis describes a series of experiments designed to investigate several aspects of aerosol dispersion and deposition in secondary flows. Aerosols encompassing a wide range of inertia are injected into turbulent and secondary flows generated in the aerosol
wind tunnel (see Child, 1992). First, velocity response experiments are conducted to investigate the particle-fluid interaction for particles encompassing a vast range of particle inertia in the approximately homogeneous turbulence developing behind a bi-plane grid. Second, the deposition rates of particles are studied in the recirculating secondary flow behind a T-step. Particle deposition rates are then scaled with turbulent and secondary flow timescales (e.g. the eddy turnover time) to determine whether the turbulent or secondary flow controls particle deposition behavior.

A study of aerosol deposition in secondary flows, however, could not be completed without addressing several integral issues. When this project was begun, a suitable facility for studying aerosol deposition did not exist in the Heat Transfer Lab; neither did a safe technique for accurately quantifying local deposition rates. Chapter 2, “Instrumentation,” describes the aerosol wind-tunnel facility and recent improvements, the Laser-Induced Fluorescence system (LIF) used to measure deposition rates, and the other measurement techniques used during the course of this thesis. A crucial facet of performing aerosol research is selecting an appropriate aerosol generation technique. Chapter 3, “Aerosol Generation,” explains the pros and cons of several methods of aerosol production considered for experiments, operational performance and details of the generators tested, and the array generator is selected for the aerosol deposition experiments.

As discussed earlier, the physics of aerosol deposition are directly related to the tendency of the aerosols to follow the flow. “Particle Velocity-Response Experiments”, Chapter 4, reviews past models and investigations of particle dispersion, and the detailed particle velocity-response experiments carried out to study the interaction of particles with turbulent flow structures. The Aerometrics Phase-Doppler Particle Analyzer (PDPA) serves as the primary tool used to quantify both particle size and velocity in the secondary
flow deposition experiments, and Chapter 4 also contains a significant assessment of the validity of the PDPA fluctuating velocity measurements.

Construction of the aerosol wind-tunnel facility, development of the experimental methods, selecting the appropriate aerosol generation technique, and investigation of particle-turbulence interaction collectively stand as an essential prelude to studying particle deposition in secondary flows. Chapter 5, "Deposition in Secondary Flow", first surveys the deposition literature and then describes the present particle deposition results in the secondary flow behind a T-step. The aerosol deposition rates in the recirculating region (i.e. the secondary flow) are compared to those of a turbulent boundary layer. In addition, appropriate time scales for particle deposition in the secondary flow and the approximately plane mixing layer downstream of the recirculation are selected.
Chapter 2 Instrumentation

This chapter describes the aerosol wind-tunnel facility and the measurement techniques used to measure aerosol deposition. First, I present the new and elongated wind-tunnel made possible by the lab renovations in the summer of 1992, including the modified contraction. Second, I detail the application of hot-wire anemometry, to measure gas phase velocities, and phase Doppler anemometry, to obtain simultaneous particle diameter and velocity measurements. Finally, I discuss potential deposition measurement techniques and their limitations, followed by an explanation of the Laser-Induced Fluorescence (LIF) technique developed to measure aerosol deposition for this thesis.

2.1 Aerosol Wind-Tunnel Facility

The Heat and Mass Transfer Lab Aerosol Wind Tunnel was originally constructed in the summer of 1991 by Child, Colmenares, and Roth (see Child, 1992). Numerous improvements have been made to the tunnel since the initial fabrication; the current tunnel is shown in Figure 2.1. The tunnel is a suction design through which flow is induced by a 0.75 horsepower blower located at the outlet. Air enters the tunnel through a straw bundle \(d_{\text{straw}} = 0.40\ \text{cm}\) bounded on both sides by 24-mesh wire screens. The bundle effectively removes large swirling structures that may arise at the entrance and also creates a uniform flow field across the section. Two additional 20-mesh screens further damp the turbulence. In the injection section, an aerosol generator seeds the flow with micron-sized water aerosols which pass into the settling section where the turbulence created by the atomizers decays before entering a 20:1 area ratio contraction. The five-foot long test section has a
variable-pitch roof to permit elimination of the streamwise pressure gradient. A 3/4 horsepower vane-axial blower creates freestream velocities of up to 13 m/s in the test section.

The initial assessments of the tunnel (see Child, 1992, and Colmenares, 1992) did not show any evidence of separation of the flow in the contraction. However, the author performed hot-wire anemometer measurements of the tunnel that found thick regions (almost 7.5 cm) of bursting activity on both the top and bottom of the entrance to the test section. Measurements at the rear of the section demonstrated that the turbulent layer had grown to span the entire height of the test section. It is not known whether the turbulent layer was present in the test section before November 1992. The wind tunnel had been disassembled during the summer of 1992 to accommodate laboratory renovations and the settling section was appended to the tunnel subsequent to those renovations and these changes in tunnel geometry may have altered the tunnel flow. To determine the cause and location of the turbulent wall layer, titanium dioxide visualization was used. TiCl₄ liquid was injected with a syringe just upstream of the mouth of the contraction. The TiCl₄ reacted readily with the moisture in the air to form very small (0.02-1.0 μm) TiO₂ particles (see Appendix C and Feng, 1994) which readily follow the streamlines of the flow. Flow visualization revealed a sizeable vortex at the mouth of the contraction and intermittent break-off and convection of the vortex into the contraction. Thus, the growing shear layer in the test section was attributed to the erratic behavior of the flow at the base of the contraction. This behavior appeared to result from boundary layer separation owing to an adverse local pressure gradient at the mouth of the contraction.

Initially, coarse (30-grit) sandpaper was affixed to the surface of the contraction to trip the flow and attempt to prevent flow separation. Unfortunately, the flow separation remained and the original contraction had to be redesigned. Several contraction geometries were tried and evaluated by measuring the thickness of the intermittent layer, δ, near
the wall. Ultimately, an elongated contraction shape that greatly smoothed the mouth of the contraction was selected (see Appendix D for the coordinates) and when installed on all four sides of the tunnel, $\delta=1.2-1.6$ cm on the bottom of the tunnel.

Boundary layer thickness measurements were used to evaluate the performance of the redesigned contraction. These measurements could not be made at the top or sides of the tunnel with the hot-wire probe, owing to probe spatial constraints. Along the bottom wall, at $x=137$ cm downstream of the test section entrance (15.2 cm from the end of the test section), $\delta$ had grown to 3.2-3.8 cm, consistent with the growth rate of a turbulent boundary layer (Schlichting, 1987) having its virtual origin in the throat of the contraction. The redesign clearly alleviated the separation problem. The vertical velocity gradient that Childs (1992) noted in his assessment of the original tunnel performance also ceased to exist.

The final contraction shape was made using inserts constructed out of 0.76 mm thick polyethylene sheet mounted with RTV Silicone Sealant onto polystyrene blocks cut to the desired contraction shape; RTV silicone sealant also affixed the polystyrene blocks to the four sides of the tunnel. Duct tape held the front and back lips of the polyethylene sheet in place and also mated the edges where four sheets intersected.

In order to gain access to the interior for altering the contraction shape, a 73 cm high by 71 cm wide access door was cut in the settling section near the beginning of the contraction. Efforts were made to insure that the wall discontinuity generated by the door did not upset the flow; there were no indications that the door did significantly disturb the flow in the test section (i.e. no evidence of flow separation). An estimate of the protrusion height, $h_p$, required to induce a turbulent transition can be made using Tani's (1969) step criterion:

\[
\frac{h_p \bar{U}}{v} \geq 825
\]  

(2.1)
Taking $\bar{U}$ in the test section to be 10 m/s (a typical operating condition), $\bar{U}$ at the door is 0.5 m/s, requiring $h_p$ to be higher than 2.5cm to effect a turbulent transition. In practice, $h_p$ was much less than one inch, indicating that the flow should not undergo transition at the door discontinuity.

Upon leaving the revamped contraction, the flow entered the new test section which has been elongated to 152cm. The roof was pinned at the front and can be pitched up at angles of over 1° to counteract boundary layer growth and maintain a constant velocity in the tunnel core. A 0.95cm wide slot extends from the front of the section to the rear to permit access of hot-wire and pitot probes to the test section. Two foam rubber strips mounted flush with the roof and centered on the instrumentation slot deform to accommodate the probes and form a seal to prevent air from entering via the slot. A 12.7cm diameter plug at the rear of the test section provided easy access to the rear of the test section.

2.2 Hot-Wire Anemometry

A TSI 1210 T1.5 hot-wire probe, mounted in a TSI probe support, was driven by a TSI IFA-100, a constant-temperature anemometer bridge circuit. The overheat ratio, OHR, is the ratio of the hot probe resistance, $R_H$, to the cold probe resistance, $R_C$. Typically, an overheat ratio of 1.8 was used:

$$OHR = \frac{R_H}{R_C} \quad (2.2)$$

The frequency response of the IFA bridge was optimized before tests per the IFA-100 1987 Instruction Manual; Fingerson and Freymuth (from Thermo-Systems, Inc., 1987) report a post-optimization cut-off frequency of at least 96kHz, well above the frequencies encountered in the present experiments. A Masscomp 5400 (with EF12M A/D boards) acquired mean and fluctuating velocity measurements using two data acquisition and pro-
cessing routines, an3.f and answ.f; the original code was composed by Kay Herbert and the two codes are substantially altered versions created by Kurt Roth. The bridge signal was low-pass filtered at 4kHz by a Precision Filters, Inc. Model 32-01-LP1; the low-pass filter is a six-pole, six-zero elliptic filter characterized by a 0.1dB band pass ripple and a roll-off of 80dB/octave.

The hot-wire was calibrated against a pitot-static probe (a MKS Baratron 398HC-0001 pressure transducer measured the differential pressure) in the tunnel. To obtain an accurate calibration, the A/D hardware and software captured 80,000 hot-wire voltages at a sample rate of 8kHz (to avoid aliasing) and averaged them. At least ten different velocity points were used in each calibration, encompassing the anticipated operating velocity range of the probe. A fourth-order least-squares curve fit, consistent with King's Law, related mean velocity to voltage.

2.2.1 A/D Discretization Error

The discretization error of the 12-bit A/D board (the EF12M) necessitated the use of the two distinctly different programs. The EF12M accepts input voltages of +/- 10 volts. Dividing this by the number of bits \(2^{12}\) yields the discretization of the incoming signal, 4.88mV. Thus, the EF12M digitizes each incoming voltage signal to an accuracy of +/- 2.44mV. Typical amplified hot-wire fluctuating voltages ranged from 0.2mV for the open test section (very low turbulence levels) up to 20mV in the turbulent boundary layers of the bottom wall. Thus, if the raw hot-wire signal of the open test section flow was acquired by the EF12M, the A/D discretization error would be an order of magnitude greater than the signal to be measured, resulting in incorrect turbulence intensities. Two approaches were taken to avoid A/D discretization errors. In the first case, program answ.f, the IFA signal
was split into two channels. The first was DC coupled. The second was AC coupled, low-pass filtered at 4kHz, and amplified by a factor of 100. Amplifying the AC component of the hot-wire signal minimized discretization errors by making the signal an order of magnitude greater than the discretization error for the smallest signals encountered. Answ.f obtained the mean velocity by summing all of the incoming DC voltages and then dividing by the number of samples to obtain a mean voltage. The AC voltages were added to the mean and each data point was converted to a velocity using a fourth-order hot-wire calibration equation.

Although the answ.f routine prevents A/D discretization errors, and effectively acquires low-level signals, it does not accurately report higher turbulent intensities, such as those found at the centerline of a turbulent air jet. A second data acquisition program, an3.f, solved the problem by using only a DC voltage channel, low-pass filtered at 4kHz and having a gain of 5. The increased gain helped to minimize discretization error, especially at higher turbulence intensities where the fluctuating signal was now greater than A/D discretization. However, a discretization turbulence intensity of approximately 0.4% still existed, rendering an3.f of limited utility for turbulence intensities of less than one-percent. Thus, answ.f was used to quantify flows with turbulent intensities less than 1.0%, and an3.f for higher turbulence intensities.

2.3 Phase-Doppler Particle Anemometry

The Phase Doppler Particle Analyzer (PDPA) is a laser doppler anemometer manufactured by Aerometrics of Sunnyvale, CA that is capable of simultaneously measuring a single component of particle velocity and particle diameter. Details of the PDPA operation can be found in The PDPA Operations Manual (Aerometrics, 1987). Bachalo and Houser
(1984) thoroughly describe PDPA theory. A velocity offset capability, produced by a rotating diffraction grating that shifts the frequency of one of the laser beams, enables measurement of negative particle velocities such as those present in reversing flows.

The transmitter and receiver of the PDPA were mounted on a rigid Newport laser platform, maintaining a consistent alignment of the transmitter and receiver. The platform was mounted on stainless steel rails oriented parallel to the flow, which in turn were attached to a Unistrut table used by Simo and Lienhard (1991), Colmenares (1992), and Child (1992). A pressurized air cylinder allows rough positioning in the vertical y-direction. Unfortunately, after much exposure to water aerosols the table had become quite warped and much effort was required to maintain the table in a plane parallel to the ground. Furthermore, the cylinder slowly leaked, causing the height and orientation of the table to drift with time. During this work, the laser platform was re-mounted on a Rambaudi machining bed in the fall of 1993. The machining bed, which is itself mounted on a 0.64cm steel plate on a pallet roller, provides much improved stability and allows positioning in the y (vertical) and z (horizontally normal to the flow) directions to a precision of +/- 0.01mm.

The PDPA measures particle velocities in the same manner as an LDA. Two laser beams, each with a power of 5mW and a diameter of 133 μm pass through the 200mm transmitter lens and converge, intercepting at the focal point to form the probe volume. The probe volume consists of alternating bands of constructive and destructive interference (i.e. bands of high intensity and much lower intensity) of the light waves known as fringes, and the fringe spacing is determined by the angle of the beam interception. As the particles pass through the bands of the probe volume, they scatter the light of variable intensity from the alternating bands: this is the doppler burst. The 495mm receiving lens collects refracted light scattered off the particles in the probe volume which it focuses upon three photomultiplier tubes (PMT) oriented in the streamwise direction. The PMT
amplifies the light signal and converts photons to a current in successive stages, and its gain is governed by the PMT voltage, \( V_{\text{PMT}} \), selected by the user. The raw voltage signal from the PMT (representing scattered light intensity) has a high frequency component representing the interference fringes and a low frequency component, or pedestal, that results from the Gaussian distribution of fringe intensity across the probe volume. Velocity measurements are derived solely from the high frequency portion of the signal, so the pedestal is removed during processing by a high-pass filter. The PDPA coprocessor electronically conditions the signal and ultimately counts the time, \( \delta t \), it takes for a pre-determined number of zero crossings, \( n_f \), to occur. Because the fringe spacing, \( X_f \), is known, the particle velocity may be easily calculated:

\[
V_p = \frac{X_f n_f}{\delta t}
\]  

(2.3)

Particle diameter measurements are obtained by studying the phase difference of the signal at three different PMTs. The light waves pass through the particle and are bent by the differing index of refraction of the particle. The longer the light wave remains in the particle the farther it propagates in the new direction; the greater the particle diameter the greater the “bending” of the light. The phase lag that exists between the different PMTs due to the light bending and the spacing of the PMTs can be expressed using Mie scattering theory in terms of the index of refraction of the particle and the medium, the geometry of the PMTs relative to the probe volume, and the particle diameter (see Bachalo and Hauser (1984) for a derivation). Because all variables except the particle diameter are known, the phase shift between the detectors yields the particle diameter. The three PMTs also provide a check on particle diameter measurement. For each burst detected, the PDPA software compares the particle diameter measurements between the first and second PMTs.
with that obtained between the first and third PMTs. If the two estimates of particle diameter differ, the software rejects the burst and ignores the measurement.

In all tests performed, the PDPA operated in the forward scatter configuration with the receiver aligned at \( \theta = 30^\circ \) with respect to the transmitter. A larger angle, such as \( \theta = 60^\circ \), would provide improved \( d_p \) resolution for smaller particles by increasing the magnitude of the phase-shift between the PMTs. However, the amount of light reaching the PMTs decreases as \( \theta \) becomes greater, reducing the signal intensity. When \( \theta < 30^\circ \), the component of reflected light increases substantially, increasing optical noise and producing more frequent measurement errors. Thus, operating at \( \theta = 30^\circ \) represents a reasonable compromise to obtain high signal quality over a range of particle diameters.

The PDPA configuration may also be optimized to look at a specific range of particle diameters by selecting one of three available transmitter beam spacings, or “tracks”. The PDPA can quantify particles over a range including particles 35 times larger than the smallest diameter selected, e.g. \( d_p = 1.4 - 50 \mu m \). Table 2.1 presents the characteristics of the three grating tracks for the lenses used (Aerometrics, 1987):

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Track 1</th>
<th>Track 2</th>
<th>Track 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>( d_p ) range, ( \mu m )</td>
<td>0.7-105</td>
<td>1.4-205</td>
<td>2.8-410</td>
</tr>
<tr>
<td>( N_f )</td>
<td>26</td>
<td>13</td>
<td>7</td>
</tr>
<tr>
<td>Beam Diameter, ( \mu m )</td>
<td>133</td>
<td>133</td>
<td>133</td>
</tr>
</tbody>
</table>

*Table 2.1: Characteristics of the PDPA Tracks.*

Proper PDPA alignment is essential to obtaining meaningful velocity and diameter measurements, as well as optimal data acquisition rates. Before beginning each experiment, the beam intersection was carefully checked and adjusted to insure that a physically
correct probe volume was created. During tests, observations made through the side por-
tals of the receiver confirmed that the probe volume was centered on the PMT slit and that
the beam interception remained true. The quality of the unfiltered and filter doppler bursts
was monitored on a 20MHz Phillips analog oscilloscope during every run. The quality of
the doppler bursts became particularly helpful in evaluating how particle deposition on the
side wall affected measurements. When signal quality was observed to have significantly
decreased, the walls were either air-dried or hand-cleaned with paper towel.

2.4 Deposition Measurement

Particle deposition on a surface can be extremely difficult to quantify. In the past, a num-
ber of techniques have been used, including dye-washing techniques (Kim 1984, Ball and
Mitchell, 1992), radioactive counting (Sweeney et al. 1990), fluorescent tracers (Zeltner
et al. 1991), and attenuation of a light source by the deposited material (Lee and Hanratty
1988). Farmer (1969) burned a ribbon of magnesium inside of a tube, coating the inside of
the tube with a fine layer of magnesium oxide where the depositing particles left a particle
diameter-calibrated imprint. He quantified deposition rate by counting and sizing the
imprints with a magnifying glass. Many of these methods are simply unacceptable for our
purposes, as they either do not provide the spatial resolution necessary for an accurate cor-
relation between deposition and the flow patterns (dye-washing techniques), would dam-
age the wind-tunnel environment (MgO) or are difficult to implement safely (radioactive
tracing). In addition, liquid aerosols tend to evaporate and may spread upon impaction,
forming thin layers that smooth out local variations in the deposition rate.

Solid particles have the advantages of eliminating the spreading and evaporation that
hamper the precise spatial resolution of liquid aerosol deposition. However, solid particles
are prone to rebounding from the deposition surface. Transmission electron microscopy (TEM) (Feng, 1994) and scanning electron microscopy (SEM) (Kucukcelebi et al., 1983) have been used to count and size the particles depositing on a surface. Microscopy techniques have the distinct benefit of permitting a direct measurement of local deposition rates. Furthermore, assuming that the particle size distribution in the flow is known, it has the advantage of admitting the use of a highly polydisperse aerosol distribution because a deposition rate can be determined for each particle size bin. Unfortunately, the cost of such techniques, TEM in particular, is prohibitive in many instances.

2.5 The LIF Deposition Measurement Technique

Nowicki (1994) developed a Laser-Induced Fluorescence (LIF) technique to measure the mass density of a deposited liquid aerosol. The method uses an aqueous aerosol doped with a fluorescent dye. Once deposited, the aerosol forms a thin liquid film on the wall, which is then probed with a laser beam. As the beam passes through the film, the dye, fluorescein, emits energy at a wavelength different from that of the incoming beam. The intensity of the laser beam light changes as it passes through the fluorescein according to Beers Law:

$$I = I_0 (1 - e^{-Ecft})$$

(2.4)

where $I$ is the outgoing laser intensity, $I_0$ the incoming laser intensity, $E$ is the molar absorptivity of the dye, $c_f$ the concentration of the dye, and $t$ the film thickness. The energy absorbed by the fluorescein dye is then:

$$I_f = I_0 e^{-Ecft}$$

(2.5)
When the term $E_{cf}$ is very small, i.e. for thin films and/or low concentrations of fluorescein dye, $I_f$ is approximately linearly related to $I_0$:

$$I_f \approx I_0 E_{cf}$$

(2.6)

It is also assumed that $E$ is constant; however, at higher laser powers, saturation of the fluorescein dye may occur, in which case increasing $I_0$ does not linearly increase $I_f$. High laser power may also cause photobleaching of the fluorescein, causing $E$ and $I_f$ to decrease over time. To avoid the pitfalls mentioned, high laser powers are avoided. Other factors, including the PMT gain, the view factor between the fluorescein and the receiving optics, and transmission losses alter the magnitude of $I_f$. Nowicki (1994) incorporated these factors, including $E$, into a constant $P$ that is determined experimentally to yield equation 2.7 for $I$:

$$I = P \cdot (I_0 E_{cf})$$

(2.7)

Figure 2.2 (Nowicki, 1994) shows the LIF system used to quantify aerosol deposition. A laser beam emanates from a tunable Lexel Argon-Ion Laser (Model 95) at a wavelength of 488nm; this is very close to the peak absorptance wavelength of fluorescein which is 490nm. After passing through interference filters, to attenuate the intensity of the beam, and a bandpass filter at 490 nm, to knock down the sidebands of the laser, the laser beam enters the SMA ferrule end of the fiber optic cable (see Figure 2.3), passing through the seven innermost fibers of the bundle. The beam exits the cable and a focusing probe manipulates the beam to achieve the proper spot size ($0.5\text{mm}^2$ used) as it strikes the deposition surface, causing the fluorescein to emit energy at a peak wavelength of 518nm. The outer twelve fibers of the bundle conduct the fluorescein signal away from the surface, along with the reflected portion of the incoming laser beam and any ambient light. Subsequently, two optical interference filters centered at 518nm extract the fluorescent signal by
blocking virtually all reflected and ambient light. The filtered light is focused onto the PhotoMultiplier Tube (PMT), a Hamamatsu side-on PMT #R928 with broad-band sensitivity between 180-900nm. The PMT translates the incoming signal, I_f, from wattage into current and a trans-impedance op-amp converts the PMT output to a voltage, V_{PMT}, while maintaining a low level of electronic noise, including “dark” noise from the PMT. Three serial 15kHz low-pass filters remove any remaining high-frequency noise from the final signal that represents the intensity of the fluorescent signal.

2.6 Calibration of the LIF System

The constants of equation 2.7 must be obtained to produce meaningful quantitative deposition measurements from the LIF system. Nowicki (1994) refined a calibration technique based on the linearization of equation 2.5, which indicates that the laser signal is proportional to c_f, I_0, E and t. Figure 2.4 shows the calibration assembly. Here, a hypodermic needle injects a small drop of the doped aerosol fluid on the bottom aluminum holder surface. A glass microscope slide rests upon the fluid and two calibrated metal shims and the top aluminum holder is placed over the slide. The two bolts are tightened, drawing the aluminum holders together to establish a gap height between the glass and the bottom aluminum holder; this ultimately is the fluid film thickness, t. The spatial uniformity of film thickness is verified by independently measuring the thickness of the holders with a micrometer and comparing their sum to the total measured assembly thickness at several locations.

The LIF probe focuses upon the fluid, the laser excites the fluorescein, and the PMT measures V_{PMT} at several points in the thin film layer. The PMT voltages are recorded for several values of t (by changing shim thickness) and c_f and plotted. Figure 2.5 displays a
calibration curve, $V_{\text{PMT}}$ versus $I_0c_f$, found by Nowicki (1994) using $c_f=0.001\%$, $I_0=0.1\text{mW}$, and $t$ ranging from 25-125$\mu\text{m}$. The slope of the calibration curve equals the coefficient $P$ in equation 2.7; Nowicki measured $P=17,100\text{ V/mW-}\mu\text{m}$ (or $P=32000\text{ mV/mg}$) with an RMS error of approximately 10%. A slight offset in $V_{\text{PMT}}$ appears due to the “dark” noise of the PMT, laser reflections that pass through the filters and ambient light conditions. Both the deposition surfaces and on the bottom aluminum holder are black to minimize laser reflection noise, improving the signal-to-noise ratio of the LIF system.

2.6.1 Photo-Bleaching of Deposited Fluorescein

If the deposited fluorescein is excited by a high enough laser intensity, the fluorescein cannot undergo further excitation and ultimately loses its ability to fluoresce with extended exposure to the excitation source. Photobleaching would tend to lower $I_f$ and therefore indicate a misleading and decreased deposition rate. To study the role that photobleaching could play in experiments, the LIF probe focused upon the deposited layer. Figure 2.6 displays the evolution of $I_f$ with time for $I_0=1.4\text{mW}$. $I_f$ exhibits a consistent decrease with time that strongly suggests an exponential response; this is consistent with the theoretical result obtained earlier for $I_f$ for non-linear response to stimulation and a decreasing value of $E$, the molar absorptivity of the fluorescein.

2.7 Surface Flow Visualization

Surface flow visualization is used to study the flow topography behind the T-step, specifically to determine the reattachment point and to assess the two-dimensionality of the flow field. Ruderich and Fernholz (1986) had significant success in identifying reattach-
ment and flow structure (e.g. corner vortices and environs) via surface flow visualization. The present technique uses a mixture of 120ml kerosene, 30ml solid TiO$_2$, and approximately ten drops of oleic acid (Roth et al., 1991). The TiO$_2$ powder is ground into fine particles with a mortar and pestle and then added to the solution. The oleic acid acts as a dispersing agent, helping to reduce clumping of the TiO$_2$ particles.

The mixture is "painted" on to the surface area of interest with a sponge brush while the test section was open. After applying the coat of mixture, the test section top was closed and the surface exposed to the desired free-stream velocity. The flow shears the mixture, drawing the mixture along the surface and leaving streaks of TiO$_2$ particles behind in the pattern of the flow. Generally, surface flow visualization is more effective at higher velocities because the shear stress is greater.
Figure 2.1: The Heat Transfer Lab Aerosol Suction Wind-Tunnel.
Figure 2.2: The LIF Deposition Measurement System.
**Figure 2.3:** The LIF Fiber-Optic Cable System.
**Figure 2.4:** The LIF Calibration System.
Figure 2.5: An LIF Calibration Curve, $I_0c_{ft}$ versus $V_{PMT}$ (from Nowicki, 1994).
Figure 2.6: Photobleaching Effect Upon Deposited Uranine Layer; \(I_0=1.4\text{mW}\).
Chapter 3 Aerosol Generation

3.1 Test Aerosol Parameters

The aerosol used for the present experiments must have several specific characteristics. First, the particle diameter must be sufficiently controllable to investigate a wide range of particle Stokes Number, $St_k$, which varies as the square of particle diameter. For deposition measurements, the aerosol should also be monodisperse, to insure that only the motion and deposition of aerosols of the correct inertia are studied; with a polydisperse aerosol, the effect of particle inertia upon aerosol deposition is far more difficult to isolate and quantify. Whereas the PDPA resolves particle diameter and velocity and is suitable for particle velocity response measurements using a polydisperse spray, a polydisperse deposited aerosol would require the use of TEM to size the particles, mandating that solid aerosols be used. Furthermore, enough aerosol must be generated to provide even and sufficiently dense seeding of the aerosol wind tunnel. A compressed air nebulizer, a condensation aerosol generator the Monodisperse Aerosol Generator (MAGE) manufactured by Lavoro E Ambiente of Italy, a Vibrating Orifice Aerosol Generator (VOAG) constructed at the Harvard School of Public Health (based on the design of the TSI VOAG), a spinning disk aerosol generator, and a two-dimensional high-power acoustic droplet generators were evaluated as aerosol sources for the deposition experiments. Polydisperse water particles generated by Vortec SprayVector atomizers were used for the grid turbulence tests.
3.2 Particle Sizing Parameters and Measures of Monodispersity

A particle distribution may be characterized by several dimensions. For example, the mean length diameter is defined as (LeFebvre, 1989):

$$d_{10} = \frac{\Sigma N_i D_i}{\Sigma N_i} \quad (3.1)$$

where $N_i$ is the number of particles of diameter equal to $D_i$. When the surface area of the aerosols is of particular interest (e.g. transport of Poly-aromatic hydrocarbons on the surface of aerosols), the surface area mean diameter would provide a more accurate characterization of the particulate:

$$d_{20} = \sqrt[3]{\frac{\Sigma N_i D_i^2}{\Sigma N_i}} \quad (3.2)$$

The volume mean diameter represents the average mass of the particles:

$$d_{30} = \sqrt[3]{\frac{\Sigma N_i D_i^3}{\Sigma N_i}} \quad (3.3)$$

whereas, the Sauter mean diameter is more appropriate for deposition purposes because it represents the ratio of particle mass to $\tau_p$ (which scales with $d_p^2$). A spray distribution in which all the particles possess the same $d_p$ is monodisperse. In reality, sprays are not completely uniform and the degree to which a spray may deviate from uniformity and still be considered essentially monodisperse is arbitrary. In practice, the monodispersity of an aerosol distribution is often characterized by the relative standard deviation or coefficient of variation, $\alpha$: 

$$d_{52} = \frac{\Sigma N_i D_i^3}{\Sigma N_i D_i^2} \quad (3.4)$$
\[ a = \frac{\sigma}{\bar{r}} = \left( \frac{\sum (r_i - \bar{r})^2 / N}{\bar{r}} \right)^{0.5} \] (3.5)

where \( \sigma \) is the standard deviation of the particle radius for the spray (Corn and Esmen, 1976). Many aerosols possess a log-normal distribution, and for these instances the standard deviation of the logarithm of the radii, \( \sigma_g \), describes the monodispersity of an aerosol distribution:

\[ \sigma_g = \left\{ \frac{\sum_i \left[ \ln \left( \frac{r_i}{\bar{r}_g} \right) \right]^2}{N} \right\}^{0.5} \] (3.6)

where \( \bar{r}_g \) is the geometric mean of the radii:

\[ \bar{r}_g = \left[ \frac{\sum_i (r_i)^N}{\Pi_i (r_i)} \right]^{1/N} \] (3.7)

When \( \alpha \) is sufficiently large:

\[ \alpha \approx \ln \sigma_g \] (3.8)

Fuchs and Sutugin (1966) suggest that a distribution is monodisperse if:

\[ \alpha < 0.2 \] (3.9)

or equivalently:

\[ \sigma_g < 1.25 \] (3.10)

For sprays that do not have a log-normal size distribution the span, \( S \), may be used to describe the monodispersity of the flow. Span quantifies the distribution of the spray mass amongst the spray particle diameters relative to the mean diameter of the spray (LeFebvre, 1989):

\[ S = \frac{d_{p_{90}} - d_{p_{10}}}{d_p} \] (3.11)
where $d_{p10}$ is the particle diameter at which the cumulative mass of all particles that
diameter or less accounts for 10% of the total spray mass, while 90% of the mass is
present in particles less than or equal to $d_{p90}$. The $S$ parameter provides an appropriate
measure of spray monodispersity when particle mass is of primary importance, e.g. in de-
position experiments. A spray with $S > 0.5$ could not reasonably be considered monodis-
perse.

3.3 Liquid Spray Atomizers

3.3.1 Pressurized Air and Water Liquid Atomizer

Two Sprayvector liquid atomizers (Vortec, Inc.) configured with a humidifying nozzle
generated water aerosols for the grid turbulence and channel flow experiments. The spray-
ers produced a highly polydisperse log-normal particle size distribution; for a typical
experimental condition, the number density of aerosols, $N_D$, in the test section was
between 100 and 150 particles/cc with the following particle size distribution (Table 3.1):

<table>
<thead>
<tr>
<th>Particle Statistic</th>
<th>$\mu$m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Diameter, $d_{10}$</td>
<td>18</td>
</tr>
<tr>
<td>Area Mean Diameter, $d_{20}$</td>
<td>24</td>
</tr>
<tr>
<td>Volume Mean Diameter, $d_{30}$</td>
<td>29</td>
</tr>
<tr>
<td>Sauter Mean Diameter, $d_{32}$</td>
<td>43</td>
</tr>
</tbody>
</table>

Table 3.1: Sprayvector Particle Size Distribution

Figure 3.1 displays a typical particle size distribution produced by the Sprayvector, as
measured in the open test section.
3.3.2 Compressed Air Nebulizer

The compressed air nebulizer constructed by Yoon (1991) was examined for potential use in deposition experiments. A 3.2mm jet of compressed air emanates from a tube and creates a low-pressure region that entrains liquid into the jet through another 3.2mm tube oriented normal to the pressurized tube. The air strongly shears the water, causing it to break into droplets. Yoon, using the PDPA to size the aerosols, determined that the nebulizer produces a polydisperse spray with $d_{32} \approx 15-16\mu m$ depending upon the air pressure.

Several efforts were made to improve the uniformity of the nebulizer spray distribution by removing larger droplets responsible for a very broad mass distribution in the spray. Initially, the nebulizer functioned in a tube 5.7cm in diameter with approximately 75 cm of travel to increase large particle removal by inertial impaction and gravitational settling. The spray possessed a polydisperse log-normal size distribution, with $\alpha \approx 0.7$ (Table 3.2):

<table>
<thead>
<tr>
<th>Particle Statistic</th>
<th>$\mu m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_{10}$</td>
<td>4.9</td>
</tr>
<tr>
<td>$d_{20}$</td>
<td>6.1</td>
</tr>
<tr>
<td>$d_{30}$</td>
<td>7.3</td>
</tr>
<tr>
<td>$d_{32}$</td>
<td>10.4</td>
</tr>
</tbody>
</table>

*Table 3.2: Particle Statistics for Yoon Nebulizer in Tube; $p_{air}=40$ psi.*

The mean diameter decreased as $p_{air}$ increased, agreeing with Yoon’s results. Two circular honeycomb matrices ($d_{h}=0.32cm$) placed in the tube 15 and 46cm from the nebulizer decreased mean diameters while apparently increasing the polydispersity of the flow (Table 3.3):
Table 3.3: Particle Statistics for Yoon Nebulizer in Tube with Two Honeycomb Matrices; $p_{air}=40$psi.

<table>
<thead>
<tr>
<th>Particle Statistic</th>
<th>$\mu$m</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_{10}$</td>
<td>3.1</td>
</tr>
<tr>
<td>$d_{20}$</td>
<td>3.8</td>
</tr>
<tr>
<td>$d_{30}$</td>
<td>4.6</td>
</tr>
<tr>
<td>$d_{32}$</td>
<td>6.7</td>
</tr>
</tbody>
</table>

A 4.5cm impaction plate, mounted with set screws at the center of the tube 20cm from the nebulizer, was tested in conjunction with a single honeycomb matrix 26cm beyond the impaction disk and $\alpha$ decreased to 0.58 (Table 3.4):

Table 3.4: Particle Statistics for Yoon Nebulizer in Tube with a 4.5cm Impaction Disk and a Honeycomb Matrix; $p_{air}=80$psi.

<table>
<thead>
<tr>
<th>Particle Statistic</th>
<th>$\mu$m</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_{10}$</td>
<td>2.5</td>
</tr>
<tr>
<td>$d_{20}$</td>
<td>2.8</td>
</tr>
<tr>
<td>$d_{30}$</td>
<td>3.3</td>
</tr>
<tr>
<td>$d_{32}$</td>
<td>4.3</td>
</tr>
</tbody>
</table>

Use of two plates slightly decreased the mean diameters, with minimal impact upon the spray monodispersity. A smaller gap between the impaction plate and the tube wall would remove an even greater fraction of the larger particles from the flow and a 5.1cm disk (i.e. halving the plate-tube clearance) lowered $\alpha$ to 0.53:
Table 3.5: Particle Statistics for Yoon Nebulizer with a 5.1cm Impaction Disk.

<table>
<thead>
<tr>
<th>Particle Statistic</th>
<th>μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_{10}$</td>
<td>1.9</td>
</tr>
<tr>
<td>$d_{20}$</td>
<td>2.2</td>
</tr>
<tr>
<td>$d_{30}$</td>
<td>2.5</td>
</tr>
<tr>
<td>$d_{32}$</td>
<td>3.2</td>
</tr>
</tbody>
</table>

The impaction discs provided reasonable improvement in the uniformity of the compressed air nebulizer and markedly reduced mean diameter values. However, they drastically depleted the mass flow rate of particles from the nebulizer to the point of very limited experimental utility.

3.4 Vibrating Orifice Aerosol Generator (VOAG)

The VOAG produces droplets resulting from the controlled forced break-up of a liquid jet (Berglund and Liu, 1973). To create a jet from the small orifices used (e.g. typically $D_j = 20\mu m$), the Weber number of the jet, $We_j$, must be greater than eight (Lienhard and Lienhard, 1984):

$$ We_j = \frac{\rho V_j^2 D_j}{\sigma} \geq 8 $$ (3.12)

Unmanipulated, a laminar jet eventually breaks up due to the shearing action of the surrounding air, resulting in a polydisperse spray. However, liquid jets have a natural breakup wavelength (thus, a natural frequency) which was first predicted by Rayleigh (1878):
\[ \lambda_{opt} = 4.508D_j \quad (3.13) \]

Schneider and Hendricks (1964) determined that by forcing the radial “sausage” mode of the jet to excite the jet at a wavelength, \( \lambda \), over rather narrow range close to \( \lambda_{opt} \):

\[ 3.5D_j < \lambda < 7D_j \quad (3.14) \]

The disturbance will grow until individual drops form, producing a uniform stream of droplets. The excitation wavelength is proportional to the driving frequency of the piezoelectric source:

\[ f_d = \frac{V_j}{\lambda} \quad (3.15) \]

The droplet diameter can be obtained by a simple conservation of mass argument to be:

\[ d_p = \left( \frac{3Q_f}{4f_d^3} \right) \quad (3.16) \]

Because the allowable values of \( \lambda \) span a factor of two and \( d_p \) varies as the cube root of the frequency (i.e. \( \lambda \)), \( d_p \) can vary by 1.26 for a given \( D_j \) and \( Q_f \).

Figure 3.2 displays a plan of a VOAG manufactured by TSI (Thermo-Systems, Inc., 1977). A syringe pump forces the aerosol fluid through the feed line, including a Millipore 0.5\( \mu \)m filter. The fluid shoots out through the stainless steel orifice, which is typically 5, 10 or 20\( \mu \)m in diameter, to form the liquid jet. The cup assembly that holds the orifice in place contains a piezoelectric ring that initiates the oscillations in the jet when excited by a AC voltage signal. By using a signal generator to match the frequency of the piezoelectric forcing with the natural frequency of the jet, a monodisperse source of droplets is obtained. Wedding (1975) produced water droplets doped with uranine dye having a \( \sigma_g = 1.06 \). Everitt and Snelling (1985) generated olive oil aerosols with \( \sigma_g \sim 1.15 \), and meth-
ylene blue solid aerosols with $\sigma_g = 1.06-1.20$. They found very good agreement between the theoretical (eqn. 3.16) and measured $d_p$.

The VOAG is not without faults. The orifices, particularly the 10 and 5 $\mu$m diameter holes, are prone to clogging. Daily purging of the system with alcohol (isopropyl alcohol was used) helped to reduce clogging; the necessity of pre-filtering the aerosol fluid and again filtering the feed line to remove any small particles that may have been created during assembly cannot be overlooked. Furthermore, the VOAG generates aerosols at a low number density, $N_d$, and a low volume flow rate, $Q_f$, because of the small orifice diameters. Typically, using the 20 $\mu$m orifice, the greatest $Q_f$ obtained was 0.086 ml/minute. Preliminary estimates of the test run length required to obtain a quantifiable level of deposition predicted test runs to endure the order of several days without evaporation, making the VOAG impractical for use in large-scale wind-tunnel experiments.

3.5 Condensation Monodisperse Aerosol Generator

Condensation aerosol generators create aerosols by taking an airflow laden with condensation nuclei and bubbling it through a heated bath of the aerosol solution. The vapor of the solution then condenses upon the nuclei to form the aerosol. Figure 3.3 displays a schematic of the MAGE, manufactured by Lavoro E Ambiente of Italy. A saline solution (0.001% NaCl by mass as recommended by Blanchard, 1993) is nebulized and the smallest aerosols are entrained in a stream of nitrogen gas. The stream is then heated to drive off the water, leaving only the salt nuclei in the stream that bubbles through the aerosol solution. A wide variety of aerosol solutions have been used to generate condensation aerosols, including DOP, DEHS, synthetic aliphatic hydrocarbon, carnauba wax, paraffin and several other types of oil; in this instance, DEHS provided by the CP Hall Co. in Chicago,
IL was used because it is non-toxic, has a very low vapor pressure, and is of a high purity (to insure consistent condensation properties). The rate of condensation of the solution upon the nuclei is directly controlled by the partial pressure of the vapor, which varies strongly as a function of temperature and volume flow rate of the nitrogen gas (see Figure 3.4 from Prodi, 1972). Therefore, by choosing the temperature of the aerosol solution and the nitrogen flow rate, the operator dictates the diameter of the aerosol particles. The heated stream of nitrogen, growing nuclei and solution vapor exits the boiler and passes through a heated tube called the reheater, which improves the monodispersity of the aerosols by heating all of the nuclei for a uniform period of time. The mixture quickly cools as it exhausts into the atmosphere.

Condensation generators such as the MAGE are valuable because they are capable of producing highly monodisperse aerosols encompassing a broad range of aerosol diameters, from 0.01µm to 8µm (Lavoro E Ambiente, 1984); Stahlhofen (1976) reports obtaining particles of up to 15 µm in diameter by using a very long condensation chimney to prolong the condensation process. Prodi (1972) generates aerosols of d_p=0.2-8µm with \( \sigma_g \) ranging from 1.02 to 1.13. Horton et al. (1991), using sodium fluorescein salt to create the nuclei for DEHS aerosols, obtains aerosols with \( \sigma_g \) varying from 1.1-1.3, depending on the bubbler temperature. The MAGE also produces a high number density is very reliable and simple to operate. Unfortunately, commercially-available condensation aerosol generators produce volume flow rates that are very low, in fact in many instances an order of magnitude less than the VOAG. For this reason, the MAGE is unsuitable for large-scale wind-tunnel testing.
3.6 Spinning Disk Aerosol Generator

Both the MAGE and VOAG produce insufficient mass quantities of aerosol to obtain measurable deposition levels in a reasonable amount of time. Spinning disk aerosol generators are capable of generating relatively mono-disperse aerosols of particle diameters greater than 7\(\mu\)m (Corn and Esmen, 1976) with mass flow rates that are orders of magnitude greater than the MAGE and VOAG quantities (in industrial applications, flow rates of tons per hour have been achieved; Corn and Esmen, 1976). Spinning disk aerosol generators have been in use for almost fifty years, and their regimes of operation and the aerosols generated are well characterized. A disk, ranging from 1 to over 30 cm in diameter, spins at speeds up to 90,000 rpm (1,500 rps). For example, Lippmann and Albert (1967) describe a 2.86 cm diameter disk spun at speeds of 350-2000 Hz to generate solid iron oxide aerosols of 1-10 microns in diameter at a relatively low flow rate (1.8 ml/minute).

A jet of the aerosol liquid impinges on the center of the rotating disk, forms a thin film on the polished surface of the disk, and convects to the outside of the disk. As the film reaches the sharp edge of the disk, it may either break into fine droplets, form ligaments (i.e. threads), or remain a film that ultimately disintegrates in the air. The regime of operation is governed by the properties of the aerosol fluid, the geometry of the disk, and the rotational speed of the disk. If:

\[
\left[4\pi\omega r \left(\frac{2\rho_p r}{\sigma}\right)^{0.5}\right]^{-0.25} \left[\frac{Q}{2r} \left(\frac{\rho_p}{\sigma^2 r}\right)^{0.5} \left(\frac{\mu}{\rho_p \sigma^2 r}\right)^{0.167}\right] < 0.00455 \quad (3.17)
\]

where \(\omega\) equals the disk rotation rate in revolutions per second, \(r\) the disk diameter, \(\rho_p\) the fluid density, \(\sigma\) the surface tension of the fluid, \(Q\) the feed rate of liquid to the disk, and \(\mu\)
the fluid viscosity, individual droplets are formed as the fluid leaves the disk (Hinze and Milborn, 1950). When the following condition is met (Corn and Esmen, 1976):

\[
\frac{\rho_p \omega^2 D_c^3}{\sigma} \left( \frac{Q}{nD_c^3} \right)^\frac{4}{3} \left( \frac{\mu D_c}{\rho_p Q} \right)^{0.19} > 0.363
\]  

film formation occurs. Otherwise, droplets are created via ligament formation and it is within this regime that most spinning disks operate. The ligaments decompose into droplets of two distinct sizes: primary droplets and satellite droplets. Typically, the primary droplets are three to four times larger than the satellite droplets and the Sauter mean diameter of all of the generated droplets equal to:

\[
d_p = 3.81 \times 10^{-5} \left( \frac{Q}{\mu} \right)^{1.48} \left( \frac{Q}{\rho_p \omega^2} \right)^{1.41} \left( \frac{\sigma \rho_p 2\pi r}{Q^2} \right)^{1.35}
\]  

The stop distances of the primary and satellite particles differ by roughly an order of magnitude and often a secondary air stream is used to entrain the satellite droplets, separating them from the primary droplets (Corn and Esmen, 1976).

The spinning disk apparatus, Figure 3.5, consists of a liquid jet impinging upon the center of the disk. The disk shaft fits into a collet attached to the driving shaft of the air motor. The air motor, a Rockwell Manufacturing Company Model S10B, can attain speeds of up to 40,000 rps (\(\omega=667\) rps) and was powered by the house air line. A pressure regulator and two valves provided control of the inlet pressure to the air motor and \(\omega\).

Initially, disks four inches in diameter were used. A circular aluminum piece, 1.25 to 1.55 cm thick was turned on a lathe to manufacture the disks. The disk possessed a flat top, which was \(-0.25\)cm thick, and a 1.27cm diameter hub with an inner diameter of 0.64cm.
(i.e. the shaft diameter accepted by the air motor) which was ~1.25cm thick. The edge the disk was beveled to sharp edge at an angle of ~30° relative to the flat top of the disk. A shaft was then machined to fit the inner diameter of the hub and the hub and shaft pinned together by a compression pin made of spring steel. When spun in the motor, no eccentricity was observed, however, a wobble mode, believed to be on the order of 0.25 mm, was present. A D=6.3 cm disk with the shaft turned as part of the disk was machined to eliminate the hub and pin and also disk wobble (see Appendix B for a discussion of disk construction and safety). The disks were polished as per the suggestion of Hinze and Milborn (1950), using 120 grit, 240 grit, 400 grit, and 600 grit sandpaper in succession. Finally, the disk was either polished on a polishing wheel using a 1 μm alumina particle finishing solution or with Noxon, a metal polishing agent, to reduce the surface roughness of the disk.

3.6.1 Performance Characteristics of the Spinning Disk Generator

The disks attain speeds much less than the maximum ω rating of the air motor. A high-speed stroboscope showed that ω_{max} for the D=6.3cm disk without fluid impinging upon the disk is 20,000rpm. Achieving a relatively monodisperse spray and a value of N_D sufficiently large to obtain quantifiable deposition proved difficult, particularly at smaller particle diameters. The following parameters were varied in an attempt to optimize the uniformity of the spray while maintaining N_D: ω, Q, and D.

Disk rotation rate has a strong influence upon d_p and film break-up regime. A solution of distilled water with 0.5% Tween-40 and 0.5% Span-20, two surfactants to reduce surface tension and improve spreading (see Section 3.9 for further details), flowed onto a 6.3cm disk at Q=0.65ml/s. Rotational rate was varied (Table 3.6), with the following affect upon particle size distribution and N_D:
Table 3.6: Spinning Disk Spray Characteristics, Q=0.65ml/s, with surfactant.

<table>
<thead>
<tr>
<th>Nominal ω (rpm)</th>
<th>d_{32} (µm)</th>
<th>d_{10} (µm)</th>
<th>N_D (particles/cc)</th>
<th>Span</th>
</tr>
</thead>
<tbody>
<tr>
<td>7,500</td>
<td>57</td>
<td>37</td>
<td>10</td>
<td>0.7</td>
</tr>
<tr>
<td>11,000</td>
<td>66</td>
<td>51</td>
<td>58</td>
<td>0.5</td>
</tr>
<tr>
<td>13,500</td>
<td>64</td>
<td>40</td>
<td>31</td>
<td>0.6</td>
</tr>
</tbody>
</table>

A different mixture, consisting of 0.075% FSN-Zonyl (another surfactant), 0.25% Tween-40 and 0.35% Span-20 impinged upon a D=6.3cm disk polished to a 1µm surface finish. The rotation rate ω was varied while Q was held constant at 0.5ml/s, producing sprays characterized in Table 3.7:

Table 3.7: Spinning Disk Spray Characteristics, Q=0.5ml/s, with surfactant.

<table>
<thead>
<tr>
<th>Nominal ω (rpm)</th>
<th>d_{32} (µm)</th>
<th>d_{10} (µm)</th>
<th>N_D (Particles/cc)</th>
<th>Span</th>
</tr>
</thead>
<tbody>
<tr>
<td>7,500</td>
<td>46</td>
<td>28</td>
<td>3</td>
<td>0.9</td>
</tr>
<tr>
<td>11,000</td>
<td>64</td>
<td>51</td>
<td>58</td>
<td>0.5</td>
</tr>
<tr>
<td>13,500</td>
<td>58</td>
<td>41</td>
<td>38</td>
<td>0.6</td>
</tr>
<tr>
<td>17,000</td>
<td>43</td>
<td>26</td>
<td>25</td>
<td>1.0</td>
</tr>
</tbody>
</table>

The spray characteristics for the two surfactant mixtures exhibit similar qualitative and quantitative trends and will be discussed together.; the span of both size distributions agrees well with the lower speed runs of Ryley (1959).

Disc rotation rate, ω, has a variable affect upon the spray mean diameters. Although d_{10} decreases with increasing ω, it appears that d_{32} is insensitive to ω. A closer examination of the other statistics suggests an explanation for this perceived trend. At 7,500rpm, a
much greater volume of fluid was observed to impact upon the side walls of the settling section at the level of the disk. Presumably, the droplets reaching the walls are very large and ballistic droplets flying off the disk that cannot be entrained in the low-speed (U~10m/s) flow in the settling section; many of the larger particles will also be lost to gravitational settling. As a result, the number density and $d_{32}$ of the spray reaching the test section are artificially low and do not accurately represent the behavior of the disk. When $\omega$ increases, $d_{32}$ was observed to remain essentially constant while $N_D$ dramatically increases. Most probably, the actual $d_{32}$ of the particles produced by the disk decreased so that many fewer particles were removed by impaction or gravitational settling before they reached the test section. At greater $\omega$, $d_{10}$ and $d_{32}$ decreased further, while the spray became distinctly more polydisperse as droplets were no longer being formed from ligaments, instead resulting from the break-up of a liquid film coming off the spinning disk. Clearly, a monodisperse spray will not result from a spinning disk operated in the liquid film formation regime.

A range of liquid feed rates, $Q$, were explored. A larger $Q$ has the advantage of producing a greater $N_D$, reducing test run length. However, if $Q$ is too great, the fluid will leave the disk as a liquid sheet and create a highly polydisperse aerosol distribution. Further tests quantified the effect of liquid feed rate, $Q$, upon $N_D$, diameter statistics, and spray monodispersity. Table 3.8 presents spray characteristics for the surfactant mixture used in Table 3.6 with the liquid feed rate more than doubled:
Overall, $N_D$ did not change appreciably with $Q$ while the high-flow diameter statistics were actually slightly lower. Increasing the liquid feed rate tends to push the spinning disk towards the film-formation regime, probably causing the high-flow spray uniformity to decrease.

Attempts were made to generate smaller particles by using a lower $Q$ (e.g. $Q\sim 0.08\text{ml/s}$) while operating at larger values of $\omega$. The resulting sprays had very low $N_D$ and were quite polydisperse. The non-uniformity of the spray distribution is thought to be a consequence of the liquid feed system to the disk. To maintain a jet impinging upon the disk surface, $W_{e_j}$ must be kept above a value of eight. This necessitated feeding the aerosol fluid to the disk surface at a relatively high velocity through a 23-gauge needle (I.D.=0.254mm). The flow inside the needle remained well within the laminar regime; however, the edge of the needle was not sufficiently even and sharp, giving the jet a three-dimensional, asymmetric quality. As a result the liquid layer forms unevenly on the surface of the disk, creating ligaments of unequal volumes which would break into non-uniform droplets. Efforts to remove the jet exit roughness and obtain a symmetrical jet failed.
3.7 Two-Dimensional High-Power Acoustic Droplet Generator

The two-dimensional high-power acoustic droplet generator (from now referred to as the Array Generator or AG) operates under principles similar to the VOAG. Unlike the VOAG, which has but one jet, the Array Generator consists of an array of orifices that are simultaneously forced (Dressler, 1989), allowing the AG to achieve a $N_d$ that is much greater than the VOAG. For example, arrays consisting of over a thousand jets have been constructed, increasing the number density of the aerosol by a similar amount (Dressler, 1993).

Figure 3.6 displays a diagram of a recent model of the Array Generator. Compressed air pressurizes the aerosol fluid in a five-gallon stainless steel tank (Alloy Products), forcing it first through a Gelman 1.0μm nominal depth filter, a Nuclepore 3.0 or 5.0 μm membrane filter and into the assembly consisting of the nozzle plates and the piezoelectric driver. The plates are fabricated of a laminated nickel-copper alloy and the orifices are etched by a technique originally conceived to manufacture printed circuit exposure masks (Dressler, 1989). Under pressure, the jets emerge from the orifices. The piezoelectric driver can be operated in a low or high power mode, with significantly different behaviors. Operating at a lower power, a Frequency Devices signal generator produces a pure sinusoid at the forcing frequency which is amplified by a MacIntosh-40 power amplifier to force the piezoelectric driver at approximately 50-60 volts peak-to-peak. The apparatus then behaves as a multi-orifice VOAG, producing monodisperse droplets over a range of diameters tunable by varying $f_d$ and the jet velocity. In the high power configuration, the frequency generator signal power is increased by a power amplifier and passes through a matching transformer before exciting the piezoelectric crystal. Acoustically "pumping"

1. Originally, 1.0μm filters were used; however, they clogged very rapidly, resulting in excessively large pressure drops and disrupting experiments when they had to be changed.
imposes much larger disturbances upon the jets, and at high enough powers causes the drops to dramatically disintegrate. As a result, the aerosol distribution produced in the high power mode is polydisperse with significantly reduced values of both $d_{10}$ and $d_{32}$ when compared to low power operation.

3.7.1 Unclogging the Array Generator Orifices

Arrays consisting of orifices as small as $20\mu$m in diameter have been constructed, and for those small diameters orifice clogging can be troublesome. This problem is particularly vexing after the initial set-up of the instrument, as small debris is inevitably generated in the assembly of fittings and opening and closing of valves; the author recommends first removing the nozzle plate assembly and flushing the system with a clean solution to purge the system after assembly and before generating particles. Fortunately, the orifice plates of the AG are far more sturdy than the delicate VOAG orifice and permit several different techniques for unclogging (Dressler, 1993). As with the VOAG, a clogged orifice can often be cleared by gently wiping the orifice with soft tissue. If the orifice remains clogged, the flush valve of the AG can be opened and pressurized air forced through the orifice (note: DO NOT use unfiltered house air!); Dressler recommends a Tech Duster compressed air can but any compressed air used for cleaning optics should suffice. The AG can also be operated in a suction mode to attempt to clear an orifice. The liquid feed valve is closed while the flush valve opened and the vacuum pump draws air through the nozzle plate orifices. The nozzle head is then submerged in CLEAN fluid from the fluid trap and the vacuum sucks the fluid through the orifices and into the fluid trap. Occasionally removing the nozzle head from the fluid allows air to pass through the orifices and...
helps to remove particulates by stirring the fluid; the combination of alternately operating in forward and suction mode proved to be quite effective in unclogging orifices.

A 225-orifice array (15 by 15 square) often has a few jets that would come out at an angle that is not normal to the nozzle plate, most likely due to a partial blockage of the orifices. These skewed jets impair the monodispersity of the array generator in two manners. First, the off-line jets move at a lower velocity than the normal jets and therefore have a different (lower) excitation frequency. However, they are still forced at the higher frequency and therefore break up into larger and probably more irregular droplets. Due to the high density of the 15 by 15 array, irregular jets tend to intercept other jets, creating multiple irregular and slower jets that also break up in an uncontrolled manner. Every effort must be made to keep all of the orifices fully unclogged.

When the orifices remain partially or completely plugged, more drastic measures should be taken to clean the nozzle plate. The nozzle head may be soaked overnight in lacquer thinner (note: this is quite a bit more potent than paint thinner!), which tends to cause many materials to swell up. The nozzle head, still in the glass jar of lacquer thinner, is then placed in an ultrasonic bath for approximately 15 minutes, followed by five (5) more minutes of ultrasound with alcohol (e.g. isopropanol) replacing the lacquer thinner as the solvent. Unlike the VOAG, the AG can be safely cleaned in an ultrasonic bath, whereas the fragility of the VOAG orifice precludes ultrasonic cleaning.

3.7.2 Dispersion Air

The uniformity of particles generated by the 225-orifice array may also be affected by impaction and coagulation. As the jet leaves the orifice, it breaks up into discrete droplets which are then slowed by drag from the surrounding, slower-moving, fluid. If one droplet
is larger than the others, or jet break-up happens slowly, the particles tend to run into each other and coagulate to form larger droplets. Dispersion air, placed at an angle to the jets, tends to minimize impaction-driven particle coagulation by deflecting the particles from a straight path. Experimenting with a variety of dispersion air angles and flow rates suggested that dispersion air aimed normally upwards towards the jet at a flow rate of approximately 1500cm$^3$/s (i.e. post-regulator line pressure of ~2.5psi) helps to optimize particle uniformity.

3.7.3 Array Generator Performance

Ideally, the array generator should produce very monodisperse spray, as it is simply a large number of VOAGs. However, particle coagulation and clogged jets do affect the practical operation of the AG, leading to variable performance. Two different particle size distributions are typically found. Figure 3.7a displays the particle size distribution measured by the PDPA just past the entrance to the test section. The spray is borderline monodisperse ($\sigma_e \sim 1.27$) with a very pronounced peak at 46μm, which is consistent with the theoretical $d_p$ predicted for an orifice diameter of 25μm; the secondary peak that appears at around 65μm, represents the coagulation of multiple particles. Table 3.9 summarizes the particle statistics for this distribution:

<table>
<thead>
<tr>
<th>Particle Statistic</th>
<th>μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_{10}$</td>
<td>54</td>
</tr>
<tr>
<td>$d_{20}$</td>
<td>56</td>
</tr>
<tr>
<td>$d_{30}$</td>
<td>57</td>
</tr>
<tr>
<td>$d_{32}$</td>
<td>61</td>
</tr>
</tbody>
</table>

Table 3.9: Array Generator Particle Statistics (I).
In other instances, the AG produces a slightly more polydisperse distribution \((\sigma_g \sim 1.30)\) with larger mean particle statistics and a much larger secondary peaks believed to result from increased droplet coagulation and incoherent breakup of slower orifices (see Figure 3.7b and Table 3.10):

\[
\begin{array}{|c|c|}
\hline
\text{Particle Statistic} & \mu \text{m} \\
\hline
d_{10} & 65 \\
\hline
d_{20} & 67 \\
\hline
d_{30} & 69 \\
\hline
d_{32} & 74 \\
\hline
\end{array}
\]

Table 3.10: Array Generator Particle Statistics (II).

The particle statistics of the array generator are very consistent within each individual deposition experiment.

3.7.4 Array Generator Aerosol Solution

Dressler (1993) recommends the solution in Table 3.11 for use in the AG:

\[
\begin{array}{|l|l|}
\hline
\text{Ingredient} & \% \text{ Mass of Solution} \\
\hline
\text{Ethylene Glycol} & 1.0 \\
\hline
\text{Dowicil 75} & 0.1 \\
\hline
\text{Sodium Borate Decahydrate (Borax)} & 0.1 \\
\hline
\text{Sodium Nitrite} & 0.1 \\
\hline
\end{array}
\]

Table 3.11: Array Generator Aerosol Fluid
Table 3.11: Array Generator Aerosol Fluid

"Hard" water would strongly corrode the AG system; thus, distilled or "soft" water should be used for the AG solution; reverse-osmosis (r-o) water (R~18Mo/cm) is used for my experiments. Dowicil 75, a preservative produced by the Dow Chemical Company, impedes microbial growth that could clog the orifices and/or the line filters. Benzotriazole inhibits galvanic corrosion of the nickel-copper nozzle plates, while Borax and Sodium Nitrite prevent galvanic corrosion from arising between the nozzle plate metals and stainless steel components. Ethylene glycol, commonly used in anti-freeze, is present as a humefactant, i.e. to coat the interior surfaces of the AG with a thin, protective layer of the preservative and buffer after the distilled water has evaporated away. Finally, sodium hydroxide or acetic acid is added as a buffer to balance the pH of the solution and minimize acidic corrosion of the nickel component of the nozzle plates.

Care should be taken to store the water in very clean containers. The r-o water is kept in jugs formerly containing alcohol. On one occasion, water that was stored in contaminated containers was used and the subsequent algae bloom ultimately clogged the line filters in a matter of a couple of minutes. The entire liquid feed system had to be purged and cleaned with isopropanol and ammonia, after which no further clogging problems were encountered.
3.8 Summary of Aerosol Generation Techniques

All of the techniques reviewed have their individual pros and cons. Figure 3.8 presents a graphical review of the uniformity, $d_p$ range, cost and $N_D$ capabilities of the five aerosol generation techniques explored. A compressed air nebulizer effectively seeds the flow with a polydisperse spray. However, the polydisperse $d_p$ distribution renders compressed air nebulizers unsuitable for correlation of deposition in flow structure. The VOAG, on the other hand, produces very monodisperse droplets while sacrificing $N_D$ and is usually limited to $d_p > 35 \mu m$; the $d_p$ range can be extended to much smaller particles by using a smaller orifice or a partially volatile solution to form liquid or solid droplets. A MAGE generates large quantities of smaller monodisperse particles, typically with $0.01 < d_p < 8.0 \mu m$; the actual mass generation rate is quite low. Spinning disk generators can operate in three regimes. In the droplet regime, monodisperse droplet production occurs, albeit at a low $N_D$. Ligament formation increases $N_D$ and creates a particle distribution that approaches monodispersity, while operation in the film formation range sacrifices monodispersity for greater $N_D$. The array generator represents a pronounced improvement in $N_D$ over the VOAG while maintaining a relatively high degree of particle uniformity. In theory, the AG should produce a monodisperse particle size distribution; in practice, this could not be achieved.

3.9 Aerosol Evaporation

The evaporation of the test aerosol was a primary concern in obtaining an accurate correlation between particle inertia and deposition rate. The Stokes Number of an aerosol whose diameter was decreasing with time would possess a time-varying particle response ($\tau_p \sim d_p^2$), resulting in inaccurate characterization of particle dispersion. Furthermore, the
deposited aerosol would be removed by convective mass transfer into the airflow, significantly reducing the measured deposition rate.

Several methods of reducing evaporation rates were explored. Numerous investigators (Sebba and Briscoe 1940, Snead and Zung 1968) have verified that long-chain fatty alcohols added to water greatly inhibit the evaporation rate by forming a thin monolayer on the surface of the water. Eisner, Quince, and Slack (1960) dispersed a solution of primarily cetyl (18 carbon chain) and stearyl (16-chain length) alcohols in water, and found that the lifetime of droplets generated by a nebulizer increased by a factor of up to several hundred. The magnitude of the increase in droplet lifetime was also shown to be dramatically greater for smaller particles. For example, in ambient air at 20°C and 80% relative humidity, a 30µm droplet’s lifetime was increased by a factor of 81 by the alcohol dispersion, while a 10µm droplet’s lifetime was 530 times longer. Davies found films of n-docosanol (22-chain alcohol) to be even more effective that the solution used by Eisner et al. Frenkiel (1965) reviewed efforts to use long-chain alcohols to retard the evaporation of water from reservoirs and to increase the temperature of rice paddies.

All of the long-chain alcohols used are not very soluble in water and therefore do not assume a uniform concentration throughout the water, instead floating at the free surface. A uniform concentration of the alcohols in the solution prior to atomization must be achieved to insure that enough fatty alcohol was present in the droplets after atomization to obtain adequate monolayer formation on each droplet. In all of the studies mentioned above, a dispersing agent, such as ether or ethylene oxide, was used to insure that the fatty alcohol was distributed evenly throughout the solution. The fatty alcohols are also known to be soluble in chloroform (CRC, 1984). However, both ether and ethylene oxide are extremely flammable and prone to explosion, and chloroform is a carcinogen, so safety considerations precluded their use.
Ultimately, a combination of two commercially available detergents, Span-20 and Tween-40, were added to the water solution to inhibit droplet evaporation. Span-20 is a 12-chain length unsaturated fatty acid ester of an anhydrosorbitol, while Tween-40 is composed of 14-chain length fatty acid ester and ethylene oxide esters of anhydrosorbitols (Hiemenz, 1986). Both are soluble in water and they compliment each other to coat the water droplet surface and reduce its evaporation surface. The long hydrocarbon chains are hydrophobic and are attracted to the surface of the droplet, whereas the ester ends of both detergents are hydrophilic and remain “rooted” in the water; the hydrophilic head of the Tween-40 is enhanced by the polyoxyethylene chains. Thus, the dual nature of both molecules is the key to their success as an anti-evaporation additive (Hatton, 1994).

FSN-Zonyl surfactant, a fluorosurfactant made by DuPont, was also explored as a possible additive to minimize the evaporation of test aerosols. Mr. Min Shyau Shu (1994) of Advanced Surface Technologies suggested using a 1% solution for the spinning disk application. The FSN-Zonyl-100 substantially improved all aspects of particle generation when compared to water without surfactant; the Tween-Span mixture generally produced a superior aerosol distribution than the FSN-Zonyl.

3.10 Evaporation Experiments

The D=6.3cm spinning disk discussed earlier generated aerosols from a solution consisting of 0.5% Span-20, 0.5% Tween-40, 0.01% fluorescein salt (uranine) and the balance \( \text{H}_2\text{O} \) at \( Q=0.5\text{ml/s} \); all percentages are stated on a mass basis. The polydisperse aerosol spray passed over a T-step mounted on the splitter plate along the horizontal center-plane of the tunnel and deposited behind the step for an hour. Using the LIF system, mass deposition measurements were made on the top surface of the splitter plate at the centerline of
the tunnel at several streamwise locations. After the initial measurement, the tunnel was
restarted; however, no further aerosol was produced. One hour after the tunnel was
restarted, the tunnel was again shut down and the deposition signal obtained via the LIF
system. The dry-run procedure was repeated three more times, with measurements made
after every hour as presented in Figure 3.9. In some instances, the data exhibits very irreg-
ular behavior, e.g. dropping precipitously after an hour and eventually rising to a higher
value than initially measured! The author noticed that a very small repositioning of the
probe (on the order of 1mm) could cause a drastic change in the strength of the LIF signal,
and suspected the erratic measurements may arise from large spatial variations in mass
deposited.

To explore this hypothesis, the probe support, placed at the centerline at x₅=10cm, was
gently jiggled so that the laser spot was very slightly displaced from its initial position;
this simulated the change in probe position between test runs. The mean fluorescent sig-
nal, $\bar{I}$, was 168mV with an RMS variation of 73mV for nine different measurements rang-
ing from a low value of 59mV and a high value of 249mV - over 300% greater! Most of
the temporal variation of $I$ was therefore attributed to the spatial variance of the deposi-
tion.

It was hoped that a longer run with a greater quantity of aerosol depositing on the sur-
face would help to average out the spatial variations in deposition found in the earlier
experiment. A test was carried out with $Q=0.5$ml/s as before; however, $c_f=0.0025\%$ was
used and the spinning disk operated for four hours, presumably increasing deposition lev-
eels by a factor of four while achieving the same amount of fluorescein deposition in the
earlier experiment. Before the test, the Sintra surface was wiped clean using first water
and then alcohol to remove the deposited fluorescein and surfactant. The dark noise of the
cleaned surface, for a incoming laser power, $I_0=0.1mW$, was 6.4mV. After running for four
hours, several deposition measurements were made at both $x_s=10.2\,\text{cm}$ and $x_s=25.4$ after similarly jiggling the probe holder. At $x_s=10.2\,\text{cm}$, $\bar{I}=557\,\text{mV}$ with an RMS variation of $18\,\text{mV}$, while at $x_s=25.4\,\text{cm}$, $\bar{I}=25\,\text{mV}$ with an RMS variation of $0.5\,\text{mV}$. The four hour test produced deposition results that were much more spatially homogeneous than the one hour test and essentially insensitive to the precise positioning of the LIF probe, clearly underscores the need for sufficiently long run times. It also indicates that the wide variations measured in the original test are due to spatial inhomogeneity of particle deposition and not film evaporation.
Figure 3.1: Particle Size Distribution of Vortec Spray Vector in Grid Turbulence Experiments.
Figure 3.2: Schematic of Vibrating Orifice Aerosol Generator (VOAG); (from Nowicki, 1994)
Figure 3.3: Schematic of Monodisperse Aerosol Generator (MAGE); (from Nowicki, 1994).
Figure 3.4: MAGE Particle Diameter as a Function of Flow Rate and Temperature (from Prodi, 1972).
Figure 3.5: The Spinning Disk System
Figure 3.6: The Array Generator (AG) System.
Figure 3.7a: Particle Size Distribution of the Array Generator (AG), mode 1, $\sigma_g=1.27$. 
Effect of Vpmt Upon Measured Droplet Diameter Distribution (High-Speed Run)

Figure 3.7b: Particle Size Distribution of the Array Generator (AG), mode 2, $\sigma_g=1.30$. 

- Vpmt = 360V
- Vpmt = 460V
Figure 3.8: Aerosol Generator Characteristics
Temporal Evolution of Deposition Signal at Several Locations Behind T-Step

Figure 3.9: Temporal Evolution of Deposition Signal at Several Locations Behind the T-Step.
Chapter 4 Particle Velocity-Response Experiments

4.1 Overview

In Chapter 4, I first examine the physics and the scaling of particle-fluid interactions. Subsequently, I present prior particle velocity-response (i.e. dispersion) models and results to motivate the work undertaken in this thesis. I then discuss the velocity response experiments I performed with water aerosols in the approximately homogeneous turbulence that evolves behind a bi-plane grid and introduce the idea of the "convective crossing trajectories effect." Because the velocity response experiments uncovered several limitations of the PDPA, I engage in a protracted analysis of PDPA error and the validity of the PDPA measurements.

4.2 The Scaling of Particle Velocity-Response

The velocity response of aerosols is governed by the tendency of a particle to follow the motion of a flow structure. The Stokes' Number, $Stk$, provides a comparison of the particle response time, $\tau_p$, to the characteristic time scale of the flow, $\tau_f$:

$$Stk = \frac{\tau_p}{\tau_f} = \frac{\text{ParticleResponseTime}}{\text{CharacteristicFlowTimeScale}}$$

(4.1)

When $Stk$ is very large, the particle will be insensitive to the flow structure and assume a ballistic trajectory. On the other hand, a particle with a very small $Stk$ will precisely follow the motion of the flow.
4.2.1 Equation of Motion for a Single Particle

Maxey and Riley (1983) rigorously derived the equation of motion for a particle in an incompressible, non-uniform flow field:

\[
m_{p} \frac{dV_{i}}{dt} = (m_{p} - m_{f})g_{i} + m_{f} \frac{Du_{i}}{Dt}_{|y_{f}} - \frac{1}{2} m_{f} \frac{d}{dt} \left[ V_{i}(t) - u_{i} \left[ Y(t), t \right] \right] - a \sigma n a \mu \left[ V_{i}(t) - u_{i} \left[ Y(t), t \right] \right] - \frac{1}{2} a^{2} \nabla^{2} u_{i} \left| y_{f} \right| \right] - 6 \pi a^{2} \mu \int_{0}^{1} \left( \frac{d}{dt} \left[ V_{i}(\tau) - u_{i} \left[ Y(\tau), \tau \right] \right] - \frac{1}{2} a^{2} \nabla^{2} u_{i} \left| y_{f} \right| \right) \right) \right) \right),
\]

(4.1)

where \( m_{p} \) represents the particle's mass, \( m_{f} \) the mass of the fluid displaced by the particle, \( V_{i} \) the particle's instantaneous velocity, \( g_{i} \) the gravitational acceleration, \( u_{i} \) the fluid velocity, \( Y \) the position of the particle at an instant in time, \( a \) the particle radius, \( \mu \) the fluid's dynamic viscosity, \( \nu \) the fluid's kinematic viscosity, \( t \) time, and \( \tau \) a past instant in time; the \( i \) subscript denotes the \( i \)-direction component of a value.

Several forces affect the particle acceleration (I): gravity and buoyancy (II), local changes in the fluid motion (III), added mass terms from the acceleration of the particle relative to the fluid (IVa) and to compensate for local streamline curvature (IVb), Stokes drag from the relative velocity of the particle and fluid (Va) with another term to describe the affect of velocity curvature on drag (Vb), and the effect of prior particle motion upon the fluid field (VI), also known as the Basset history term. Shear forces (e.g. the Saffman lift force from a velocity gradient normal to the direction of particle motion) and particle rotation have been neglected; if present, the Saffman lift force can significantly influence deposition rate (Fan and Ahmadi, 1993). The particle's motion is also assumed to be independent of flow boundaries. In practice, the majority of the terms of eqn.4.2 are negligible and may be dropped; Maxey and Riley (1983) present criteria describing the relative significance of the individual terms. When both \( \text{Re}_{p} << 1 \) and the particle density greatly
exceeds that of the fluid, such as for a water aerosol in air, eqn. 4.2 reduces to a balance of particle acceleration against particle drag (III) and, for a particle settling in still air, gravity (II).

4.2.2 Particle Time Scale

An appropriate choice of $\tau_p$ is the viscous stopping time of the aerosol, which represents the approximate time it would take a particle to react to a velocity difference between the aerosol and the fluid continuum. The stopping time of a particle can be derived from a simple force balance of particle drag, $F_D$, and particle inertia. When the particle Reynolds Number, $Re_p$, is much less than unity, the drag equals the result for Stokes flow around a sphere (Schlichting, 1987):

$$F_D = 6\pi \mu r V_p$$  \hspace{1cm} (4.3)

When the particle is either very small (on the order of the molecular scale where the fluid can no longer be considered a continuum) or large (where $Re_p \sim O(1)$ or greater) the Stokes' drag law no longer applies, and corrections must be made to reflect the change in particle drag. For particles much smaller than the mean free path of the environment, $\lambda$, (typically, $\lambda \sim 50\text{nm}$ (Fuchs, 1964)), the drag on the particle may be represented as (Fuchs, 1964):

$$F_M = \frac{-6\pi \mu r V_p}{(1 + A r \frac{r}{\lambda})}$$  \hspace{1cm} (4.4)

For particles where $r \sim \lambda$, an empirical result (Milikan (1923) and Knudsen and Weber (1911) from Fuchs (1964)) for drag should be used:
where $A$, $K$ and $b$ are experimentally determined coefficients.

When $Re_p \sim O(1)$, an appropriate expression for particle drag (Oseen, 1927 from Fuchs, 1964) is:

$$F_M = -6\pi \mu r V \left(1 + \frac{br}{1 + A \frac{r}{l} + K \frac{l}{r}} \right)$$

(4.5)

If a particle moves through a still fluid with an initial velocity, $V_0$, the fluid’s viscosity dissipates the particle’s momentum until the particle ultimately comes to rest. The particle relaxation time, $\tau$, represents the time constant of the particle to reach the fluid velocity. Assuming that Stokes drag law is indeed valid (Fuchs, 1964):

$$F_M = -6\pi \mu V_p \left(1 + \frac{3}{16} Re_p \right)$$

(4.6)

$$\tau_p = \frac{2 \rho_p r_p^2}{9 \mu}$$

(4.7)

where $\rho_p$ represents the density of the aerosol, $r_p$ the particle radius, $V_p$ the relative velocity between the particle and the fluid, and $\mu_f$ the fluid viscosity. The distance a particle will propagate into the fluid is termed the stop distance, $l_i$, of the particle:

$$l_i = V_0 \tau_p = \frac{2 V_0 r_p^2 \rho_p}{9 \mu}$$

(4.8)
4.3 Flow Time Scale

Researchers unanimously agree that the particle relaxation time is the definitive particle time scale for \( Stk \). However, an appropriate choice of the fluid time scale is not universally obvious. A common model for \( \tau_f \) of very inertial particles (Crowe 1988, Hestroni 1989) assumes that a particle is primarily influenced by the most energetic eddy in the flow and uses the inverse of that frequency for \( \tau_f \) irrespective of the particle’s inertia. Longmire and Eaton (1992) injected rather massive glass spheres in an axisymmetric jet and observed particle dispersion via laser imaging techniques. They successfully scaled particle dispersion with the large-scale turbulent structures and observed that the particles tend to cluster between vortex ring structures in regions of low vorticity and are flung radially outwards as they encounter the large-scale flow structures. Lazaro and Lasheras (1992) demonstrated that the large-scale turbulent motions appear to govern particle dispersion in a developing free shear layer.

Another approach, taken by Wells and Stock (1983), proposes scaling marginally inertial particle behavior with the Kolmogorov time scale, \( \tau_K \), the timescale of the smallest structures of a turbulent flow:

\[
\tau_K = \frac{v}{\varepsilon}
\]  

(4.9)

The authors successfully scaled small particle response behavior with \( \tau_K \) whereas earlier efforts had used the most energetic eddy timescale. Simo and Lienhard (1991) also employed \( \tau_K \) to describe the response of moderately inertial particles in a decaying air jet. It is quite possible that proper scaling of eddy-particle interaction may lie somewhere between the large eddy timescale and the Kolmogorov time scales. By examining the
behavior of particles of differing inertia in a decaying turbulent flow, a better understanding of eddy-particle interaction may be achieved.

4.4 Models for Particle Velocity Response

Hjelmfelt and Mockros (1966) apply the Basset equation to a particle moving through an infinite, stationary, viscous fluid. They model particle dispersion by assuming that the particle is completely entrained in a single eddy and numerically solve for the particle dispersion relative to that of the carrier phase for particles comprising a range of diameters and densities. From these results, they predict the relative magnitudes of the terms of the Basset equation and for what \( \tau_f \) the particle motion accurately represents that of the fluid. Furthermore, they show that a particle cannot have a greater fluctuating velocity, \( v' \), than the fluid phase and obtain curves describing a steep roll-off of particle velocity response with increasing \( St_k \).

Much effort has been put forward towards studying the “crossing-trajectories effect.” The “crossing-trajectories effect” refers to a particle moving from a region of the flow field where it is well correlated with the flow field to a less correlated region. For instance, a particle convected by a flow in a direction normal to gravity will experience the “crossing-trajectories effect.” The particle will be influenced by the eddies it initially encounters and will attempt to follow these eddies; the particle will be correlated (i.e. follow the eddies) as well as the particle’s inertia permits. With time, gravity causes the particle to tend to descend and to depart from the initial eddies it experienced for other flow structures. The particle, whose trajectory was created by the former eddies encountered, is now less correlated with the local, “new” eddies. This effect becomes more pronounced for greater particle inertia, as a longer timescale inhibits the particle from following the newly
encounter eddies. The higher settling velocity of a more inertial particle compounds the loss of correlation by causing the particles to enter and leave flow structures more often.

Snyder and Lumley (1971) measured particle velocity autocorrelation functions for particles encompassing a range of particle inertia settling under the influence of gravity in the approximately homogenous turbulence behind a bi-plane grid. They found that particle inertia depressed velocity autocorrelation functions and that the decrease was more pronounced for more inertial particles. Wells and Stock (1983) completed experiments very similar to Snyder and Lumley to study the “crossing trajectories” effect upon particle dispersion. Their experiments also demonstrated that the gravitational forces reduced particle velocity correlation, particle dispersion and $v'$ were attenuated for more inertial particles. Maxey (1987) simulated the settling of a particle in a homogeneous turbulence field under the influence of gravity and confirmed the trends of both groups.

Maxey (1987) also found that particles tend to concentrate in regions of low vorticity and high strain, a result corroborated by Squires and Eaton (1991) in their simulation of particle dispersion in isotropic turbulence. Sommerfeld and Qiu (1993) came to a similar conclusion based their experimental and numerical simulations of particle dispersion in a swirling flow. Rudoff et al. (1989) measured local number densities in a swirl stabilized burner using a PDPA and discovered that the local $N_D$ could vary by an order of magnitude or more in a period of only a few milliseconds. They ascribe the large fluctuations to the unsteadiness of the flow field and particle clustering in regions of low vorticity.

4.4.1 Velocity Response Augmentation

Several experimentalists have quantified instances where particle velocity response (i.e. rms velocity) can exceed that of the flow, contradicting the result of Hjelmfelt and
Macros (1966). Physically, one could imagine a particle with \( \tau_p \sim \tau_f \) tenuously entrained in the eddy that would be eventually "centrifuged" from the eddy, resulting in particle dispersion being greater than that of the fluid. Chien and Chung (1987) examined the dispersion of aerosols in a turbulent shear flow generated by a discrete vortex method. Using the vortex-paring time scale, they predict that moderately inertial aerosols \( (0.5 < St_k < 5.0) \) undergo a greater mean dispersion than the fluid phase, in some instances observing particles being thrown from the vortices; they conclude that the greatest particle dispersion occurs within an intermediate range of \( St_k \). Hishida et al. (1992) measured the dispersion of glass beads in a turbulent mixing layer and found that particle behavior scaled well with \( St_k \) based on the large-scale eddies. They also confirmed that particle dispersion for these larger particles exceeded that of the gas phase, i.e. enhanced particle dispersion, while possessing lower levels of fluctuating velocity in both the streamwise and cross-flow directions.

Moderately inertial aerosols may also experience enhanced velocity response in decaying turbulent flows. Simo and Lienhard (1991) took an Eulerian approach to the equations of particle motion. They obtained a first order solution of the equations of motion for a particle with \( \tau_p \ll \tau_K \) in a homogeneous turbulence flow field that predicts a small increase in \( v' \) over \( u' \) (less than 1%) over a range of values:

\[
\frac{v'}{u'} = 1 + 2 \left( \frac{\nu_K}{u'^2} \right) \left( \frac{\tau_p}{\tau_K} \right) + O \left( \frac{\tau_p}{\tau_K} \right)^2
\]

where \( \nu_K \) represents the velocity of the smallest eddies of the flow, the Kolmogorov velocity:

\[
\nu_K = \left( \nu \varepsilon \right)^{\frac{1}{4}}
\]
Implicit in their equation is that the Kolmogorov length scale, $l_K$, is much larger than $d_p$:

$$l_K = \frac{\frac{3}{4} u^4}{1} \approx d_p$$

(4.12)

Experimental studies of aerosol response in decaying jets (Simo and Lienhard, 1991) and approximately homogeneous grid turbulence (Colmenares, 1992) raise the possibility that more significant elevation of particle response, of up to 10 or 20 percent, may be realized for some particles.

4.4.2 Comparison of Experiment with Numerical Models

Few researchers have successfully achieved good agreement between velocity response codes and experiments. Lu et al. (1993) obtained rather good agreement between their Lagrangian model of the particle-turbulence interaction and experimental data. Sommerfeld and Qiu (1993) carried out experimental and numerical (k-$\varepsilon$) simulations of particle dispersion in a swirling flow, finding inconsistent agreement between the particle fluctuating velocities. Call and Kennedy (1992) applied a particle imaging technique to measure particle dispersion in a turbulent, round air-jet. A numerical stochastic simulation of particle dispersion displayed qualitative, yet mediocre quantitative agreement with the experiments. Ounis and Ahmadi (1990) computed moderately inertial particle dispersion in a turbulent Gaussian velocity field. Their model predicted a roll-off of particle diffusivity as $St_k$ increased that was qualitatively similar to that of Hjelmfelt and Macros (1966) but substantially less than measured in past experiments (e.g. Snyder and Lumley, 1971). However, Squires & Eaton (1991) numerically simulated particle dispersion in an isotro-
pic turbulence field and found particle diffusivity to exceed that of the flow for each case.

In sum, the numerical results, although they may have in many instances a sound physical basis, do not show universal correlation with experiment.

4.5 Bi-plane Grid Turbulence Experiments

The flow field produced by a sufficiently developed grid turbulence is well suited for studying the velocity response of moderately inertial aerosols in a decaying flow. After a flow passes through a biplane grid with mesh size $M$, a region of approximately homogeneous turbulence is established beyond about $x=15M$ downstream of the grid. Homogeneous turbulence and the scaling of the turbulent energy decay has been understood for quite some time (Batchelor, 1953) and is well quantified. Fluctuating velocity measurements of the fluid phase at successive stations downstream of the grid yield the decay rate of the flow and permit calculation of $\tau_K$ and $St_k$ at any streamwise location in the developed flow region.

The decay of the developed grid turbulence flow field in the streamwise direction has been shown by several authors (e.g. Compte-Bellot and Corrsin, 1966, Batchelor and Townsend (1948) from Hinze, 1975) to follow a power law:

$$\left(\frac{u}{u^*}\right) = A \left(\frac{x}{M} - \frac{x_0}{M}\right)^n$$

(4.13)

where $M$ is the mesh length and $x_0$ the virtual origin of the region of virtually homogeneous turbulence. $A$ and $n$ are constants that are determined experimentally; typically, the exponent $n$ lies between 1.0 and 1.2 (Hinze, 1975). Because the flow field beyond the virtual origin (i.e. $x=15$ to $30M$) can be considered to be approximately homogeneous and
isotropic, the streamwise evolution of the turbulent dissipation rate, $\varepsilon$, is characterized by the following relationship (Colmenares, 1992):

$$
\varepsilon = \frac{3n}{2A} U^3 M^n (x - x_0)^{1-n}
$$

yielding the Kolmogorov time scale from eqn. 4.9.

In the present experiments, a bi-plane grid with $M=1.59\text{cm}$ and 33% solidity was used initially (the same as Colmenares, 1992); however, the relatively small mesh spacing resulted in short decay lengths and made locally resolution of the flow difficult. It also evoked the spectre of the more inertial particles "lagging" the decay of the flow field, creating a situation where $\tau_p$ would be of the order of the time scale of the flow decay and violate the approximation of locally homogeneous turbulence. For most of the experiments, a bi-plane grid with $M=0.038\text{m}$ and a solidity of 37% was used to permit finer spatial resolution of the turbulent flow field and improve the local homogeneity of the flow by decreasing the spatial rate of decay of the flow. Thus, the decay time scale was much larger than the particle time scales, insuring that the local $\tau_K$ could be used to characterize particle behavior.

A hot-wire anemometer measures the spatial decay of the developed turbulent field behind the bi-plane grid and a least-squares fit calculates the constants of the decay law. Colmenares (1992) used a PDPA to quantify the turbulent flow field; in light of the PDPA error in $v'$ and the superior ability of the hot-wire to measure lower turbulence intensities, a hot-wire was employed. Figure 4.1 displays a typical results for the decay law of the grid turbulence. The constants obtained, $A=46$ and $n=1.086$ with a virtual origin of $x_0=5$, are consistent with prior experimental results (Batchelor and Townsend (1948) from Hinze (1975), Compte-Bellot and Corrsin, (1966)).
The PDPA measures $V_p$ and $v'$ over a range of particle sizes. Before a true comparison of particle and fluid fluctuating velocity can be made, it is necessary to determine which particles follow the flow and therefore represents the behavior of the fluid phase. In other words, the smallest $d_p$ that accurately represent the gas phase in an experiment can be established by measuring at what particle diameter the particle velocity response begins to deviate from the behavior of the smallest particles that must follow the flow. Towards this goal, the initial experiments were performed with the PDPA configured on track 3 to measure $d_p$ ranging from 0.7 to 25$\mu$m (0.7$\mu$m being the smallest $d_p$ resolved by the PDPA). Figure 4.2 plots $v'/u'$ versus $St_k$ (i.e. velocity response) for the aforementioned range of particles at various distances behind the grid. The flatness of the curves over the entire spectrum of $d_p$ verifies that the smallest particles do indeed trace the flow for this speed and mesh size and that they provide an accurate measurement of the gas phase turbulence. In all subsequent results, $u'$ will always connote the fluctuating velocity of the gas phase as measured by the smallest $d_p$ bin. The flat velocity response for $d_p<25\mu$m also implies that enhanced or depressed velocity response may occur for particles possessing a greater diameter than $d_p=25\mu$m.

Figure 4.3 presents velocity response plots, $d_p$ vs. $v'$, at several streamwise locations in a decaying turbulent field for $d_p=1.3-50\mu$m; $U=9.6$m/s. Note that the curves are essentially flat at all streamwise locations for $d_p<20\mu$m. The flow timescale, $\tau_f$, increases as the turbulence decays and more representative picture of velocity response may be gained by examining a graph of $v'/u'$ squared versus $St_k$ (Figure 4.4); the data, as will all subsequent PDPA grid turbulence results, reflect a correction for the apparent PDPA "RMS error", explained in Appendix B. This log-normal plot indicates that particles with $St_k<0.1$ have an essentially flat response, which is consistent with the definition of $St_k$: $\tau_p$ is much less than $\tau_f$, so the particles should have sufficient time to react to any fluctuations.
in the flow field. In terms of $d_p$, one can confidently assume that, for the conditions encountered in the developed grid turbulence region, $d_p<5\mu m$ particles accurately reflect the gas phase.

Returning to Figure 4.4, at $St=0.1$, particle velocity response begin to gently roll-off at most streamwise measurement stations. Qualitatively, a similar result is predicted by Hjelmfelt and Mocros (1966), whose analytical results suggest a more precipitous decline in particle response with $St_k$. The behavior of the larger particles is quite interesting. Examining the curve for $x/M=20$, the velocity response remains quite flat until $d_p=40\mu m$ or $St_k=0.5-1.0$, when it actually begins to increase. Further downstream, a similar trend arises. Not only does the augmentation occur at smaller values of $d_p$ and $St_k$, but it also increases in magnitude. Quite clearly, the change in velocity response cannot be explained by sole consideration of $\tau_K$, as the $(v'/u')^2$ vs. $St_k$ curves do not agree in either the $St_{krit}$ nor the degree of heightened response. The behavior of the large, more-inertial particles, contradicts past models and warranted further investigation.

4.5.1 The “Convective Crossing Trajectories Effect”

One hypothesis to explain the high-inertia particle behavior is that the particles are so large and inertial that their motion is not properly scaled with $\tau_K$. Instead, a larger time scale, such as the most energetic scale, $l_e$, or even the largest scale of the flow, that established by the grid, $\Lambda_M$, may be more appropriate. A plausible explanation is that the velocity response of the larger particles lags that of the flow. The bulk flow convects particles possessing a $v'$ from a region of the flow closer to the grid, where $u'$ is greater, into a region of the flow where $u'$ is lower. The particles, due to their large $\tau_p$, do not have sufficient time to “adjust” to the new flow, and their behavior is primarily dictated by their his-
tory. Thus, the inertial particles will have a higher level of fluctuation than the gas phase at a given streamwise location. I will term this effect the "convective crossing trajectories effect" to reflect the role that bulk convection plays in the transport of the particles from a region of higher to lower fluid turbulence intensity.

If the "convective crossing trajectories effect" does indeed describe the streamwise evolution of particle behavior, several trends would be expected to arise. First, the velocity response data of the inertial particles would be expected to qualitatively collapse to scale with the ratio of $\tau_p$ to $\tau_M$ for all streamwise distances beyond the point where the developed approximately homogeneous turbulence field has been established. This scaling would approximate a scaling with $\tau_p$, as the streamwise evolution of $\tau_M$ is quite slow. Second, the magnitude of the apparent spatial augmentation in velocity response should increase in its streamwise evolution (Regime 1) until the flow has decayed where $\tau_M$ is of the order of $\tau_p$ (Regime 2); this would occur because the convective lag between the particle with $v'$ and the ever-decreasing $u'$ of the fluid would grow. Third, $v'$ would at last reflect $u'$ of the flow when $\tau_p<<\tau_M$ (Regime 3); the interpretation of Figures 4.2 and 4.4 with respect to the smallest particles following the flow would suggest that this limit is reached when $\tau_p/\tau_M$ is of the order of 0.05-0.1. Figure 4.5 graphically summarizes the three regimes of velocity response predicted by the "convective crossing trajectories effect" model.

4.6 Detailed Grid Turbulence Experiments

A thorough effort was made to understand the increase in $v'$ uncovered in the earlier grid turbulence experiments, particularly the behavior of larger particles. The PDPA was used to measure $v'$ at locations ranging from $x/M=13$ to 32 with the same grid detailed above.
Statistical certainty was a primary concern. The earlier particle response data exhibit levels of fluctuation which made quantification of velocity response difficult, although qualitative trends were still discernible. Towards this end, twenty runs were taken at each streamwise location, with each individual run consisting of roughly 60,000 velocity measurements and enduring from five to ten minutes. A run was halted if it reached ten minutes in length in order to minimize an artificial $v'$ created by a potential drift in $\overline{U}$, the freestream tunnel velocity, of the motor (see Section 4.91 for further discussion of this phenomenon). The tunnel walls were frequently wiped with paper towels\(^1\) between runs to clean and dry the surfaces through which both the laser and the scattered light passed.

Each plot of the streamwise evolution of particle velocity-response consists of over 10 million (10,000,000) data points of size characteristics and distribution similar to Figure 3.1 and Table 3.1. The PDPA operates on track3, with the greater interception angle of the beams increasing the number of fringes, $N_f$, and also improving the resolution of smaller particles. Preliminary tests found that the spray contains few particles greater than 80\(\mu\)m, so the software was set to acquire velocity statistics in the range $d_p=2.3\text{--}80\mu m$; note that the smallest particles are well below the $d_p=5\mu m$ cut-off established in the initial grid turbulence experiments for a particle to accurately reflect the flow field. On average, the $d_p=80\mu m$ bin contained approximately 50 particles per run, the fewest particles of any bin, while the smaller diameter bins each held several thousand particles. Thus, each data point on a particle response graph is obtained by considering between $O(10^3)$ and $O(10^5)$ individual particle velocity measurements.

In the introductory remarks about velocity response, I mentioned that $l_K$ should be much greater than $d_p$. In the grid turbulence experiments, $l_K$ ranged from approximately

\(^1\) Bounty is preferred to reduce long-term microscratch damage to the transparency of the plexiglass (Quinn, 1993).
166µm at x/M=6 to 274µm at x/M=274, indicating that an appreciable quantity of larger particles probably did not satisfy this criterion. Thus, the velocity augmentation result predicted by Simo and Lienhard (1991) would not apply to the larger particle.

Figures 4.6a-i display particle response versus \( Stk \) at x/M=16-32. The effect of averaging the data over thousands of points has clearly reduced the scatter of the data. The particle response qualitatively resembles the results of the initial experiments. At low \( Stk \), the response curves are rather flat and begin to exhibit a slight decrease in \( v' \) relative to \( u' \). Farther downstream, the more inertial particles exhibit response augmentation that grows dramatically with x/M, which would be consistent with the proposed concept of “convective crossing trajectories” effect.

The particle response graphs, despite the large number of data points, do not yield smooth curves, flying in the face of the decay in velocity response predicted by (Hjelmfelt and Macros, 1966). An unexplainable phenomenon also arises in the experiments, a pronounced decrease in \((v'/u')^2\) that consistently appears near the top end of the range of \( Stk \) investigated. This “notch” does not correspond to a particular value of \( Stk \). so particle response is plotted versus \( d_p \) to ascertain if the notches correlate well with a specific \( d_p \). Figures 4.7 a-i display particle response versus \( d_p \) and it becomes quite clear that the “notch” regularly appears at \( d_p \approx 60\mu m \). Furthermore, more careful inspection reveals a secondary dip in particle response near \( d_p = 35\mu m \). The term “notch” is quite appropriate for the sudden declines in \((v'/u')^2\), as locally the plot resembles the frequency response of a notch filter with the center frequency equal to the \( d_p \) reported above. However, the author can think of no plausible fluid mechanical phenomenon that could reproduce such response in a particle-fluid system. Thus, the notches are thought to be artifacts of the PDPA measurement system, as described next.
4.7 Investigation of Particle Response Notches

4.7.1 PDPA Operation on Track 2

The PDPA operates with one of three rotating grating tracks, with a lower numbered track capable of sizing larger particles with an offsetting decrease in resolution of $V_p$; all the tests presented so far were with the PDPA set on track 3. It was hoped that changing the track number would remove the notch while validating the response found in the track 3 experiments.

Towards this end, the PDPA was set to operate on track two and particle response at $x/M=22$ was measured. As before, I performed twenty test runs, each consisting of approximately 60,000 particle velocity measurements. Figure 4.8 a-c display the track 2 results. The response curves are very smooth and the notches which contaminated the track 3 experiments have apparently disappeared. However, the track 2 measurements of particle response are markedly different than the track 3 measurements, i.e. the $d_p$ dependence of particle response magnitude is different for the two tracks. To evaluate the consistency of the track 2 result, the PDPA was used to process twenty runs of ~60,000 velocity measurements at $x/M=30$; the track 2 $x/M=30$ curve, Figure 4.8c, lacks notches above the noise of the data and has a somewhat different character than the track 3 result. In fact, both track 2 curves are very similar in shape in magnitude despite a significant difference in streamwise position and turbulence levels.

Figure 4.9a compares the uncorrected turbulence intensities (i.e. the pythagorean correction technique (see Appendix C) was not applied) versus $d_p$ measured by tracks 2 and 3 at $x/M=22$, while Figure 4.9b shows the corrected turbulent intensities. Although tracks 2 and 3 measure almost identical initial turbulence intensities for the smallest particles, track
2 consistently reports a greater v'/U than track 3. Figure 4.9c plots particle velocity response for the two tracks (normalized to v'/U of the smallest particles) and fully reveals the magnitude of the difference between the two tracks: track two, in this instance, measures the particle dispersion to be, in many instances, more than 40% greater than track two, implying 40% greater particle streamwise rms velocity. Clearly, track 2 and track 3 obtain significantly different velocity response results.

Operating the PDPA in the track 2 configuration successfully removed the particle response notches observed on track 3 while opening Pandora's Box: track 2 measured markedly different particle response result than track 3. The response appeared to be independent of x/M, and therefore turbulence intensity. Table 4.1 summarizes the differences between tracks 2 and 3:

<table>
<thead>
<tr>
<th>Track 3</th>
<th>Track 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>“Notches” in response curves</td>
<td>No “notches” found</td>
</tr>
<tr>
<td>Particle response evolves with x/M</td>
<td>Particle response apparently independent of x/M</td>
</tr>
<tr>
<td>U~U\text{pitot}</td>
<td>U~0.95U\text{pitot}</td>
</tr>
<tr>
<td>Lower Measurements of N_D</td>
<td>Higher values of N_D</td>
</tr>
<tr>
<td>Smaller probe area</td>
<td>Probe area 20-40% larger</td>
</tr>
</tbody>
</table>

**Table 4.1:** Comparison of Track 3 and Track 2 Velocity Response Data

The following questions begged for answers: Which track is more accurate and yields a more accurate portrayal of particle response? Why do the notches occur on track 3 but not track 2?
4.7.2 Aerometrics' Assessment of Track 2 versus Track 3

Mr. Dave Carr, an engineer with Aerometrics, studied the configuration of the PDPA and recommended operating at a higher counting frequency\(^1\) to remove the notches on track 3 (Carr, 1993). Unfortunately, Figures 4.10 a-d indicate that increasing the counting frequency did not remove the notches found on track 3. Upon further investigation, Aerometrics explained that the notches probably result from an error related to the measurement of phase, i.e. particle diameter. The PDPA processor records the phase lag of a particle's signal between two PMTs and when the phase difference is greater than 360°, the counter resets and begins counting at 0° again. The diameter at which the phase passes 360° and is reset is called the “phase transition.” Aerometrics explained that two of the phase transitions occur on track 3 at around \(d_p=35\mu m\) and \(d_p=60\mu m\) - coincident with the velocity response notches. Sankar and Bachalo (1990) report that in some instances particles with \(d_p\sim O(d_b)\), where \(d_b\) is the laser beam diameter, may be reported as even larger particles, raising the possibility that the \(d_p=60\mu m\) notch may reflect the lower values of \(v'\) observed at smaller \(d_p\). However, nothing in the \(d_p\) histograms suggest that this may have occurred. The mechanism by which a phase transition could artificially depress \(v'\) is not known.

4.7.3 Open Tunnel Runs

An understanding of the PDPA response at relatively low turbulence levels was needed in order to assess the feasibility of velocity response experiments. The notches

\(^1\) The counting frequency was varied in the software setup by changing the “n” exponent on Alt-f, page 3, to 1 from its former value of 0, for track 3 measurements.
found in the track 3 experiment, evidently an artifact of the PDPA hardware and/or software, make track 3 unsuitable for relatively low turbulence level measurements and suggest further study of the PDPA on track 2. A fundamental test was to generate water particles with the Vortec sprayers with an open test section (without grid), and determine how the PDPA interpreted $v'$ for a range of $d_p$, i.e. to establish a baseline "error" for track 2 of the PDPA.

The sprayers, as measured by a hot-wire with dispersion air and no water flow, create a turbulence level of approximately 0.7% in the center of the tunnel. With the PDPA set on track 2, eight runs of ~60,000 $V_p$ measurements each yielded the particle response curve displayed in Figure 4.11a. Figure 4.11b and c represent additional track 2 tests at different streamwise locations including more than twice as many runs per test.; an extended range of x-locations were chosen to determine if the accelerating flow in the contraction would affect particle dynamics, e.g. if the response of the larger, more inertial particles would evolve in time. All three curves have very similar shapes with slight variations in the offset of the ordinate. Furthermore, the curves bear an eerie resemblance to the shape of the track 2 grid turbulence results of Figures 4.8 a-c; again, the primary difference is one of ordinate offset. The grid turbulence levels at $x/M = 22$ are measured at 3.2% by the hot-wire, which is substantially greater than the ~0.7% $u'/U$ measured at the open channel centerline, yet the particle "response" curves given by the PDPA are very similar. Hot-wire measurements also show that the decay of the turbulent field behind the grid scales very well with $M$ (see Section 4.5), indicating that the grid dictates the flow field, implying that the flow field is independent of the sprayers.

The striking similarity of the open channel and grid turbulence particle response experiments leads to the conclusion that, for relatively low turbulence levels, the PDPA configured on track 2 does not accurately measure particle response because the error of
the instrument, which is non-linear with respect to particle diameter, overwhelms the
effect of the turbulence upon the particles.

4.7.4 Track 3 Open Channel Runs

Prior to discovering the PDPA misalignment, the open channel performance of track 3
was evaluated for \( dp < 25 \mu m \), i.e. particles that should follow the smaller motions of the
flow. Twenty-two runs produced a mean value of \( v' \approx 1.5 \) for \( dp < 3.3 \mu m \), suggesting that the
track 3 RMS error inherent in the PDPA approaches 1.5%.

4.7.5 Viability of Track 3 Results

The notches found in the velocity response measurement of track 3 are worrisome, but
can probably be dismissed as an artifact of the PDPA data acquisition system, i.e. the
curves may be considered to be continuous with the notches removed. The track 3 velocity
response curves, unlike the track2 measurements, also show a distinct evolution with \( x/M \)
which can be supported by the "convective crossing trajectories" argument explained ear-
lier (in Subsection 4.5.1). An open test run with track 3 for \( dp = 2.3-80 \mu m \) needs to be per-
formed to evaluate the dependence of \( v' \) error with \( dp \).

However, the fact that the track 3 grid turbulence velocity response curves evolve con-
siderably with \( x/M \) suggests that the crossing trajectories effect, at least in a quantitative
sense, is relevant to the particle velocity response in the decaying flow behind a bi-plane
grid.
4.8 Conclusions

The grid turbulence experiments find qualitative evidence of the “crossing trajectories effect,” i.e. the rms velocity of the particle decaying at a rate slower than that of the flow and the particle convecting to a region of lower turbulence intensity, causing the particle to locally have a greater rms velocity than the fluid phase.

A quantitative measurement of the magnitude of the particle rms lag could not be made with confidence, owing to the error of the PDPA rms velocity measurements. A substantial effort was undertaken to uncover the magnitude and operating parameter dependence of the PDPA $v'$ measurement error; Appendix D, “PDPA Error” presents the experiments and the results in detail. In short, the “background rms” measurement of the PDPA appears to be about 1.5% and has a distinct signature that increases with both $d_p$ and $V_PMT$. Appendix D also contains a literature review of the PDPA error.

Appendix E, “Channel Flow Experiments” summarizes the velocity-response experiments that were carried out in the higher turbulence levels encountered at the centerline of a fully-developed channel flow, with the hope being that the higher turbulence levels would minimize the effect of the PDPA error upon the results. They did not appear to do so.

In light of the PDPA shortcomings unearthed in the quest to particle response dynamics, the velocity response experiments were terminated. Specifically, the non-linearity of $v'$ error with $d_p$ and the persistence of the error at the higher turbulence levels (e.g. at the centerline of a fully-developed turbulent channel flow) rule out the use of the Aerometrics PDPA for studying particle velocity response in well-controlled low turbulence flows.
Figure 4.1: The Spatial Decay of Grid-Turbulence; $A=46.2$, $n=1.086$. 
Figure 4.2: Initial Grid Turbulence Particle Response Experiments at Several x/M Locations; uncorrected for PDPA error.
Figure 4.3: Initial Grid Turbulence Fluctuating Particle Velocities versus $d_p$ from $x/M=16$ to 30; uncorrected for PDPA error.
Figure 4.4: Particle Velocity-Response for \(x/M=16-30\); corrected for PDPA error.
Figure 4.5: Graphical Representation of the Crossing Trajectories Effect.
$x/m = 16, \ x = 0.61m$

Figure 4.6a: Grid Turbulence Particle Velocity Response versus $Stk$, $x/M=16$. 

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Figure 4.6b: Grid Turbulence Particle Velocity Response versus $Stk$, $x/M=18$. 
Figure 4.6c: Grid Turbulence Particle Velocity Response versus $Stk$, $x/M=20$. 

$x/m = 20, \; x = 0.76m$
Figure 4.6d: Grid Turbulence Particle Velocity Response versus Stk, x/M=22.
Figure 4.6e: Grid Turbulence Particle Velocity Response versus Stk, x/M=24.
Figure 4.6f: Grid Turbulence Particle Velocity Response versus Stk, x/M=26.
Figure 4.6g: Grid Turbulence Particle Velocity Response versus Stk, x/M=28.
Figure 4.6h: Grid Turbulence Particle Velocity Response versus $Stk$, $x/M=30$. 

\[ x/m = 30, \ x = 1.142m \]
Figure 4.6i: Grid Turbulence Particle Velocity Response versus $St_k$, $x/M=32$. 

\[
x/m = 32, \quad x = 1.22m
\]
Figure 4.7a: Grid Turbulence Particle Velocity Response versus $d_p$, $x/M=16$. 

$x/m = 16, \ x = 0.61m$
Figure 4.7b: Grid Turbulence Particle Velocity Response versus $d_p$, $x/M=18$. 
Figure 4.7c: Grid Turbulence Particle Velocity Response versus $d_p$, $x/M=20$. 

$x/m = 20$, $x = 0.76m$
Figure 4.7d: Grid Turbulence Particle Velocity Response versus $d_p$, $x/M=22$. 

\[ x/m = 22, \ x = 0.84m \]
Figure 4.7e: Grid Turbulence Particle Velocity Response versus $d_p$, $x/M=24$. 

$x/m = 24$, $x = 0.915m$
Figure 4.7f: Grid Turbulence Particle Velocity Response versus d_p, x/M=26.
Figure 4.7g: Grid Turbulence Particle Velocity Response versus \(d_p\), \(x/M = 28\).
$x/m = 30, x = 1.142m$

**Figure 4.7h:** Grid Turbulence Particle Velocity Response versus $d_p$, $x/M=30$. 
Figure 4.7i: Grid Turbulence Particle Velocity Response versus $d_p, x/M=32$. 

$x/m = 32, \ x = 1.22\text{m}$
Figure 4.8a: Track 2 Grid Turbulence Particle Velocity Response versus $d_p$, $x/M=20$.  

$x/m=20$, $x=0.76m$ 7/1/93, grating #2
Figure 4.8b: Track 2 Grid Turbulence Particle Velocity Response versus $d_p$, $x/M=22$. 

$x/m = 22$, $x = 0.84$ m grating #2, 7/2/93
$x/m = 30, \quad x = 1.142m; \quad PDPA$

Figure 4.8c: Track 2 Grid Turbulence Particle Velocity Response versus $d_p, \quad x/M=30$. 
Comparison of Track 2 and Track 3 Turbulent Intensities Uncorrected for PDPA Error; x/M=22.

Figure 4.9a: Comparison of Track 2 and Track 3 Grid Turbulence Intensities versus d_p, x/M=22; uncorrected for PDPA error.
Comparison of Track 2 and Track 3 Turbulent Intensities Corrected for PDPA Error.

Figure 4.9b: Comparison of Track 2 and Track 3 Grid Turbulence Intensities versus \( d_p, x/m=22 \); corrected for PDPA error.
Comparison of Track 2 and Track 3 Turbulent Intensities Corrected for PDPA Error and Normalized.

Figure 4.9c: Comparison of Track 2 and Track 3 Particle Velocity-Response versus $d_p$, $x/M=22$; corrected for PDPA error.
Figure 4.10a: Track 3 Grid Turbulence Particle Velocity-Response versus $d_p$, with $n=1$, $x/M=18$. 

$x/m = 18$, $x=0.68m$, 26 July, 1993; track #3, n=1.
Figure 4.10b: Track 3 Grid Turbulence Particle Velocity-Response versus $d_p$, with $n=1$, $x/M=22$. 

vlj93, $x/m=22$, $x=0.84m$. Track#3, $n=1$. 19 July, 1993
Figure 4.10c: Track 3 Grid Turbulence Particle Velocity-Response versus $d_p$, with $n=1$, $x/M=24$. 

$x/m = 24, x=0.915m, 26$ July, 1993; track #3, $n=1$. 

\[ \frac{(v' / u')^2}{D_p, \text{ microns}} \]
Figure 4.10d: Track 3 Grid Turbulence Particle Velocity-Response versus \( d_p \), with \( n=1, x/M=30 \).
Chapter 5 Deposition in Secondary Flow

5.1 Overview

Chapter 5 begins by examining existing aerosol deposition models and past aerosol deposition results. I introduce the choice of the T-step geometry to experimentally study deposition in a secondary flow and discuss the secondary flow field behind a T-step. Lastly, I present the experimental secondary flow deposition results and examine the appropriate aerosol and flow field parameters to scale deposition rate.

5.2 Turbulent Inertial Deposition and Deposition Velocity

Numerous investigators have come up with a variety of models for aerosol deposition from a turbulent flow field. A useful concept for quantifying aerosol deposition is the deposition velocity, \( V \), which represents the ratio of mass deposition rate, \( J \) (kg/m\(^2\)s) to the mass density, \( C_D \), of aerosols of a given diameter in the flow:

\[
J \approx C_D \]  

(5.1)

The deposition velocity may also be expressed in viscous units\(^1\), \( V_+ = k_D u_+ \). Friedlander and Johnstone (1957) assume that a particle will deposit from a turbulent flow if the particle possesses sufficient momentum to pass through the quiescent flow of the viscous sublayer, \( \delta_+ \), of the turbulent boundary layer, i.e. if the stop distance of the particle, \( l_i \), is

---

1. Viscous units are obtained by scaling the parameter with the parameters governing the boundary layer structure near the wall, i.e. \( u_+ \) and \( v_+ \). To convert a length to viscous units, multiply the length by \( u_+ \) and divide by \( v_+ \). For a velocity, divide the velocity by \( u_+ \).
greater than $\delta_v$. An eddy deposition model may then be developed relating $V_+$ to a dimensionless particle relaxation time, $\tau_+,$ representing the ratio of particle to turbulent flow time-scale:

$$\tau_+ = \frac{u^2 \tau_p}{\nu} \quad (5.2)$$

They assume that outside of the viscous sublayer, the fluctuating component of velocity normal to the wall, $v'$, is the cause of particle deposition and is a constant value in all regions of interest. Translating $v'$ into viscous units, Friedlander and Johnstone show the stop distance, in viscous units, to equal:

$$l_{i+} = v' + \tau_{p+} \quad (5.3)$$

Thus, when a particle has sufficient inertia to carry it through the viscous sublayer, i.e. when $l_i=\delta_v$, the particle will impact upon the surface.

Friedlander and Johnstone’s (1957) model does not take into account the variation of $v'$ in the boundary layer, broadly approximating $v'$ to be independent of the distance from the wall, $y$. Davies (1966) proposed a more rigorous approach to predicting particle deposition rates. He incorporated detailed turbulent pipe flow data from Laufer (1954) into his model to obtain $v'$ as function of the distance from the wall, $y$. In viscous units:

$$\frac{y}{v'} + = y' + + 10 \quad (5.4)$$

This expression may be combined with the dimensionless form of eqn. 5.1 (in viscous units) to obtain $V+$:

$$V_+ = v' + N_{D+} = N_{D+} \left( \frac{y}{y'} + 10 \right) \quad (5.5)$$

which can be translated into a dimensionless stop distance:
\[ l_i+ = v' + \tau_p + \]  

One half of all aerosols at a given location with sufficient inertia, i.e. such that \( l_i+y_+ \), will deposit on the wall surface.

The deposition theory of Davies (1966) unfortunately tends to underestimate \( V+ \) by up to two orders of magnitude (Liu and Ilori, 1974). Liu and Ilori modeled the particle diffusivity, \( \varepsilon_p \), defined as:

\[ J = \varepsilon_p (N_D - c_w) \]  

where \( c_w \) is the concentration of aerosol at the wall (typically assumed to be zero). They expressed \( \varepsilon_p \) as the sum of the turbulent (fluid) diffusivity, \( \varepsilon \), and the tendency of the particle to not completely follow the trajectory of the flow. They assumed that an eddy initially entrains a particle, implying that the particle at first has the same diffusivity as the fluid. As the eddy approaches the wall, the eddy breaks down into smaller eddies and the particle is flung from the initial eddy with the momentum imparted by the original eddy, i.e. \( v' \). The particle travels a distance equal to \( l_i \) before it comes to rest. Thus:

\[ \varepsilon_p = \varepsilon + v \tau_p \]  

which agrees quite well with experimental deposition measurements made by Friedlander and Johnstone (1957) for aerosols with \( 0.1 < \tau_+ < 10 \) in a turbulent pipe flow. It bears repeating that their theory assumes that the aerosol is completely entrained in the initial eddy, thus limiting the validity of their model to moderately inertial particles (i.e. \( \tau_+ < 100 \)).

Wall roughness changes the shape of the turbulent boundary layer, particularly in the region in proximity to the wall (Hama (1954), from Schlichting, 1987) and complicates calculation of a deposition rate. Depositing particles change the profile of the surface, creating a temporally evolving roughness that causes deposition rate to also change as a function of time. Wood (1981, from Fan and Ahmadi, 1993) and Papavergos and Hedley
(1984, from Fan and Ahmadi, 1993) found that roughness, even quite small, substantially increased deposition rates. Im and Ahluwalia (1989) produced numerical simulations of aerosol deposition and determined that even hydraulically smooth flow can amplify deposition rates, particularly for less inertial particles. Fan and Ahmadi (1993) proposed a sublayer model for particle deposition in a turbulent duct flow, taking into account the coherent vortices near the wall in addition to the drag, lift and gravitational forces. Their numerical results agree rather well with past experiments and suggest that surface roughness can increase the deposition rates of moderately inertial aerosols by up to two orders of magnitude. However, the movement of aerosols with $\tau_+$ equal to ten or greater are rather unaffected by the near-wall turbulence structure. Thus, the deposition rates for those particles are relatively unaffected by all but the largest roughness elements (Fan and Ahmadi (1993) and Im and Ahluwalia (1989)).

5.2.1 Past Turbulent Deposition Results

McCoy et al. (1977) and Lopes (1986) (from Griffith, 1990) display a wide range of turbulent deposition data, scaling the dimensionless deposition rate with Stokes Number, $Stk$, based upon turbulent timescale, i.e. with $\tau_p/\tau_f$ (see Figure 5.1). The data can be separated into three distinct regimes of particle behavior. For low $Stk$, deposition occurs almost uniquely due to diffusion of the particles through the viscous sublayer. At $Stk\sim0.2$, the deposition rate increases precipitously with $\tau_p/\tau_f$ due to the onset of turbulent impaction of particles; the particles begin to deviate from the motion of the flow and deposit on the surface. The deposition rate continues to increase with $Stk$ until $Stk\sim20$, at which point the particles cease to follow the swirling motions of the flow and the deposition rate levels off. Note that the data typically exhibit scatter of approximately one order of magnitude, indi-
cating the difficulty of consistently and accurately measuring deposition and also suggesting that deposition may have a statistical description. Im and Ahluwalia (1989) present turbulent deposition results using the scaling parameters arrived at by Friedlander and Johnstone (1957) (Figure 5.2) and observe a similar degree of scatter.

5.3 Step Flows

A forward-backward facing step provides a well understood secondary flow structure that has been investigated thoroughly and is well characterized (O’Malley et al. 1991, Castro and Haque 1987, Ruderich and Fernholz 1986, Kiya and Sasaki 1985, Chandrsuda and Bradshaw 1981, Eaton and Johnston 1981, Bradshaw and Wong 1972, Roshko et al. 1965). It is a particularly appropriate geometry in that it also mirrors many of the practical applications motivating this study (i.e. partial lung blockage, erosion behind weld seams). As a particle-laden flow passes over a step, the flow separates from the top of the step and a large recirculating vortex forms behind the step. The motion of particles is strongly affected by this vortex (Kim et al. 1984, Ruck and Mikiola 1988). Subsequently, the flow reattaches at a distance approximately six step heights downstream of the step (Chandrsuda and Bradshaw, 1981).

Ruck and Mikiola (1988) used laser doppler anemometry to compare the mean and fluctuating velocities of glass spheres of 1,15,30 and 70μm diameter flowing over a backward facing step and found that the larger particles tended to not track the flow as accurately as the smaller particles; larger particles also universally possessed reduced values of v’ and v in the recirculation region. Because the propensity of an aerosol to respond to flow structures has been shown to scale with Stk, it follows that the deposition rate of moderately inertial particles in a secondary flow would also scale with a form of Stk. An
appropriate $\tau_f$ for a step flow might well be the inverse of the eddy turnover time. As with the turbulent case, the secondary flow $St_k$ describes tendency of particles to follow the flow and thus resist deposition due to inertial mechanisms.

5.4 Secondary Flow Behind a T-Step

5.4.1 Mean Flow

A T-shaped step (Figure 5.3) is chosen as the preferred geometry to investigate aerosol deposition from a secondary flow. The Reynolds Number based on step height, $Re_{hs}$, ranges from approximately $1.4 \times 10^3$ to $2 \times 10^4$; for future reference, $Re_{hs} \approx 1.4 \times 10^4$ in the experiments of Ruderich and Fernholz (1986), while Castro and Haque made measurements for $Re_{hs} < 2 \times 10^4$. Figure 5.4, taken from Ruderich and Fernholz (1986), presents a three-dimensional view of the flow streamlines. The flow passes over the T-shaped step mounted on the front of a splitter plate and separates off the top edge of the T. Further downstream, the flow reattaches to the splitter plate, locally elevating the wall pressure (Farabee, 1986). The primary motivation for selecting a T-step over a backward facing step, is the longer mean reattachment length of the T-step which provides better spatial resolution of the flow structures and the deposition resulting from the particle-flow interaction. Typically, the mean reattachment length, $x_r$, varies between:

$$6h_s \leq x_r \leq 9h_s \quad (5.9)$$

described by Ruderich and Fernholz (1986) and Castro and Haque (1987) has a much longer \( x_r \), ranging from values of:

\[
17h_s \leq x_r \leq 23h_s
\]  

(5.10)

Castro and Haque (1987) argue that the general features of the flow bounding the recirculation region are somewhat similar to that of a shear layer bounding a substantial recirculation zone, and compare many of their mean and fluctuating measurements to those found in a plane mixing layer. After reattachment, the flow undergoes a period of readjustment before it reestablishes a fully developed turbulent boundary layer.

5.4.2 Two-Dimensionality of Flow

In creating a separating, reattaching flow to study particle-flow-deposition interaction, great care must be taken to minimize the three-dimensionality of the flow. Ruderich and Fernholz (1986) suggest several criteria for obtaining a separating, reattaching flow region that is approximately two-dimensional (independent of the transverse \( z \)-direction) at and near the centerline of the splitter plate. The no-slip condition at the walls of the tunnel side walls necessarily introduce a transverse component to the flow field. De Brederode (1975, from Ruderich and Fernholz, 1986) discovered that the flow behind a backward-facing step or a blunt splitter plate is essentially two-dimensional as long as the aspect ratio of the tunnel width, \( w \), to \( h_s \) is greater than 10. However, Ruderich and Fernholz, using the T-step geometry discussed earlier, found the flow to be strongly three-dimensional, with large corner vortices forming near the wall-step intersection, for an aspect ratio of 22, and suggested that the ratio of \( w \) to \( x_r \) might provide a superior parameter to assess the two-dimensionality of the flow field. Their attempts to use splitter plates to isolate the affects of the wall boundary layer upon the separated region and subdue the corner vortices had

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the opposite affect, instead increasing the three-dimensional nature of the reversed flow and doubling the number of corner vortices.

The ratio of \( h_s \) to the half-tunnel height, \( y_t \), also affect the separated flow structure. Smits (1982) and Ruderich and Fernholz (1986) establish that higher levels of step blockage reduces \( x_r \) while increasing the height of the reattachment bubble; Kiya and Sasaki (1983) indicate that the unsteadiness of the reversed flow region also rises with increased flow blockage. Higher free-stream turbulence intensities tend to decrease \( x_r \), e.g. an increase in \( u'/U \) from 0.2% to 0.4% produces a 5% decrease in \( x_r \) (Kiya and Sasaki (1983)). Ruderich and Fernholz (1986) measured the lateral variation of longitudinal wall-shear stress, \( \tau_w \), with a Preston tube, \( \bar{U} \), and \( u' \) at streamwise distances up to 2.6\( x_r \) downstream of the T-step. They found little variation in all three parameters within 0.2w of the centerline. Ruderich and Fernholz also measured a reversed-flow parameter, \( \chi \), that quantifies the percentage of time during which reversed-flow occurs. At \( x_r=0.52 \), \( \chi \) remained essentially constant at \( \chi=0.9 \) within 0.4w of the centerline at \( y=0.66h_s \), and within 0.2w at \( y=2.2h_s \). Taken together, the results of Ruderich and Fernholz imply that despite potent corner vortices arising at the edge of the plate, the flow field can be considered approximately two-dimensional within 0.2w of the centerline.

5.4.3 Turbulence Quantities

The recirculating eddy dominates the middle and outer layers of the bubble and its structure is independent of \( Re_{h_s} \). The separation bubble possesses a high degree of unsteadiness and turbulence. Velocity spectra are not typical of a turbulent flow, lacking a distinct spectral peak that could be identified as the most-energetic eddy frequency (Ruderich and Fernholz). Furthermore, the spectra contain an additional and large low-fre-
quency component representing the secondary flow time scale (Castro and Haque) probably due to the streamwise movement of the reattachment point, also known as "flapping"; the experiments of Ruderich and Fernholz, operating at a lower Rehs than Castro and Haque and overlapping Rehs of these experiments, do not report evidence of "flapping." At the core of the main vortex, the mean velocity attains values equal to 0.3U with a local turbulence intensity reaching 50%.

Closer to the wall, the local skin friction scales with Rehs (Castro and Haque) and the flow resembles a laminar boundary layer with a favorable pressure gradient. In addition, large regions of the separated flows exhibit velocity profile similarity (Ruderich and Fernholz). However, a true boundary layer does not exist in the recirculation zone, nor after reattachment, as the flow does not satisfy the "law of the wall".

5.5 Present T-Step Configuration

A plexiglass step, machined to a 30° angle on the edges (see Figure 5.3), mounts to the front of a 1.59cm thick splitter plate consisting of a plexiglass plate sandwiched between two pieces of black Komatex and Sintra plastic. Several T-step configurations are obtained by varying hs. Step heights ranged from 2.54cm to 0.64cm, corresponding to longitudinal aspect ratios from 9 to 36 and blockage ratios from 4.2 to 16.8, where the blockage ratio, B, is defined as the ratio of the tunnel cross-sectional area to the cross-sectional area of the T-step:

\[ B \equiv \frac{A_{Ctun}}{A_{Cstep}} \]  

(5.11)
5.5.1 Reattachment Length

Surface flow visualization with a mixture of kerosene, TiO2, and oleic acid provides a global view of the flow behind the T-step. Figures 5.5a, b, c and d are photographs of the recirculation region taken for several values of \( h_s \) and \( U \). The images provide information about the two-dimensional nature of the flow. Near the T-step, the large corner vortices at the intersection of the side walls and the T-step, identified by Ruderich and Fernholz (1986), are clearly shown in Figure 5.5a (\( h_s = 1.27 \text{cm}, \ U = 12.65 \text{m/s} \)). However, Figure 5a and Figure 5b (\( h_s = 2.54 \text{cm}, \ U = 9.70 \text{m/s} \)) both suggest that the flow beyond the region immediately behind the step is two-dimensional near and at the centerline, with some transverse curvature occurring near flow reattachment. The reattachment length is usually readily visible. For example, the reattachment region can be seen in Figure 5c (\( h_s = 1.27 \text{cm}, \ U = 12.65 \text{m/s} \)) as the accumulation of TiO2 particles at a mean streamwise location of \( x \approx 8'' \). The low-speed flow visualization \( x_r \), for example Figure 5d (\( h_s = 2.54 \text{cm}, \ U = 3.5 \text{m/s} \)), may not be quite as clear as in the faster runs. Indeed, the “blurring” of the reattachment locus may result from the low streamwise \( \tau_w \) at reattachment, or indicate low frequency unsteadiness in the location of flow reattachment referred to as “flapping”. The “flapping” phenomenon has been observed by other authors (e.g. Kiya and Sasaki (1983), Castro and Haque (1987)). Table 5.1 presents \( x_r \) for the three step heights studied and at three different freestream velocities as determined from the visualization:

<table>
<thead>
<tr>
<th>( h_s )</th>
<th>( U ) (at ( x=6'' ) fore T-step)</th>
<th>( x_r )</th>
<th>( x_r / h_s )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.635</td>
<td>13.30</td>
<td>14</td>
<td>22</td>
</tr>
</tbody>
</table>

*Table 5.1: T-Step Reattachment Length as a Function of \( U \) and \( h_s \).*
The reattachment length varies greatly with step height while decreasing slightly at lower U. The unusually low reattachment lengths measured for the 2.54cm step (the survey of Ruderich and Fernholz (1986) finds that generally \(17 < x/x_r < 23\)) most likely results from the small aspect ratio between the step (X= 4.3) and the tunnel half-width (Smits (1982) and Ruderich and Fernholz (1986)). The higher free-stream turbulence levels induced by the dispersion air and the wake of the array generator system (i.e. the nozzle holder, fluid lines, and system support mount) would also tend to decrease \(x_r\) (Kiya and Sasaki, 1983); the \(x_r\) measurements exhibit little, if any, effect of upstream turbulence upon \(x_r\).

The mean flow velocity decreases as step height increases due to the additional blockage presented by a larger T-step.

### 5.6 Particle Deposition Experiment Protocol
Before each test run, the black sintra plastic surface was cleaned several times with wet and dry paper towels to remove the fluorescein from the surface to reduce the background signal from the deposition surface. After the room lights were turned off (to minimize the ambient light signal), the laser power, \( I_0 \), was first recorded and then \( V_{\text{PMT}} \) at all of the streamwise locations where the deposition rate was to be measured. The laser was operating at the very low end of its power rating (~0.15mW out of a possible 8W) and was prone to drift; to obtain a reliable "baseline" \( V_{\text{PMT}} \), the laser power was rechecked after measuring \( V_{\text{PMT}} \) at all streamwise locations, re-measuring \( V_{\text{PMT}} \) at all stations if \( I_0 \) varied by more than +/-20% from the mean over the course of the measurements. Generally speaking, turning on the laser for at least ten minutes before making measurements minimizes drifts in \( I_0 \).

The Array Generator (AG) produced aerosols in the settling section (approximately 70cm before the mouth of the contraction) using the fluid prescribed by Dressler (1993) doped with fluorescein; the fluorescein concentration was \( c_f = 0.01\% \) by mass. Typically, the AG operated at a manifold pressure of either 15 or 25psi, while the piezoelectric elements were forced at 78 or 118kHz respectively. After the aerosols passed through the contraction and into the test section, the PDPA measured particle size characteristics and number density, \( N_D \), at a streamwise location 15cm in front of the T-step, vertically positioned at the top lip of the step, and at the transverse centerline.

The particles pass over the step, and after a run (usually one hour long), the LIF system (see Section 2.6) measures the amount of deposited fluorescein. As during the ambient measurements, the room lights were kept off and the laser power recorded both before and after the tests; the test deposition measurements were repeated if \( I_0 \) varied by more than 5%.
Using the calibration constant obtained in Section 2.6, the LIF signal is converted to a deposition layer thickness, $t$ (in cm), and translated into a deposition velocity:

$$ K_D = \frac{J}{C_D} = \frac{t \left( \frac{\rho_f}{t_r} \right)}{\rho_f d_{30}^3 N_D} = \frac{t}{d_{30}^3 N_D t_r} $$

(5.12)

where $C_D$ represents the density of the aerosols in the carrier fluid, $d_{30}$ the volume-mean particle diameter and $t_r$ is the run time in seconds.

5.6.1 Particle Evaporation Correction

In this and all other experiments, an attempt was made to correct deposition measurements for evaporation. Aerosol particles which have partially evaporated before they reach the test section have a higher concentration of fluorescein because the same volume of fluorescein remains in the droplet while the aerosol’s volume decreases by evaporation of water. An estimate of the magnitude of particle evaporation can be gained by looking at the particle size distribution produced by the array generator. The distribution always has a pronounced peak corresponding to the natural break-up of the fluid jets. All of the deposition experiments were performed with the AG operating at a line pressure of 14psi at a forcing frequency of 78kHz, with an array of 25μm diameter orifices. For successively higher speed test runs (i.e. less time for evaporation to affect $d_p$), the peak $d_p$, $d_{\text{peak}}$, converged to $d_p=46-47\mu m$. This value agrees well with VOAG theory for the range of allowable $d_p$, and $d_p=46\mu m$ was taken as the reference particle diameter, $d_{pr}$. It was then assumed that the change of $d_{pr}$ between the generator and the test section was indicative of the evaporation of the entire spray. Naturally, this overestimates the effect of evaporation upon larger droplets; however, a significant shift in $d_{pr}$ was only noticed for lower speed
runs where a much larger portion of the large droplets were removed from the airflow by
gravitational settling. Following through with this model yields a correction coefficient,
$C_{f_{cor}}$, for the deposition velocity, $K_D$:

$$C_{f_{cor}} = \frac{d_{peak}^3}{d_{pr}^3} = \frac{K_{D_{corr}}}{K_D}$$  \hspace{1cm} (5.13)

to account for the increase of $c_f$ due to evaporation. Figure 5.6a (no correction) and Figure
5.6b (with correction) show the effect of $C_{f_{cor}}$ upon data; typically, $C_{f_{cor}}$ only impacts
lower-speed experiments (i.e. $U<8$m/s), i.e. when the particles have a longer residence
time during which they can evaporate. The smallest coefficient obtained was $C_{f_{cor}}=0.28$
for the turbulent boundary layer experiments, and $C_{f_{cor}}=0.32$ for the T-step experiments,
both for $U<4$m/s. A large number of the higher speed tests had $C_{f_{cor}}=1.0$.

### 5.7 Turbulent Boundary Layer Deposition Rates

The flat plate used for the T-step experiments was also used to measure deposition
rates in a turbulent boundary layer. Kiya and Sasaki (1983) measured the reattachment
length on the top and bottom of a blunt plate of thickness $H$ and found $x_r=10H$, indicating
that for $H=0.95$cm, $x_r=9.5$cm. To reduce the size and possibility of flow separation, the T-step
was removed and replaced by a rounded leading edge. Initial experiments produced
significant puddles of fluid just behind the leading edge which would shed large droplets
that subsequently deposited upon the plate, thus producing unreasonably high deposition
rates. A two-ply paper towel was taped over the leading edge of the plate, absorbing the
fluid at the leading edge. The array generator, operating at a line pressure of 14psi with the
piezoelectrics driven at 78kHz, produced aerosols in the settling section which were con-
vected into the test section. Deposition measurements were made with the LIF system at
x=37.5, 40, 42.5, 70.6, 73.1, 75.6, and 78.2cm, i.e. distances ranging 3 to 7 x_r downstream
of the reattachment point predicted by Kiya and Sasaki (1983). The rounded and rough-
ened edge counteracts the tendency of the flow to separate at the leading edge, lending cre-
dence to the belief that the flow would undergo a milder separation or avoid separating
entirely, and recover to the state of a turbulent boundary layer by the time it reached the
deposition measurement stations.

The PDPA measured particle and flow statistics 15.3cm fore of the plate and also
40cm downstream of the leading edge, both at a height 3.2cm above the plate. The nose
presumably trips the boundary layer to a turbulent state, and past turbulent boundary layer
particle deposition scalings (e.g. Griffith (1990), Lee et al. (1989)) should apply. These
scalings are known to collapse the existing turbulent deposition data into three distinct
regimes (see Figure 5.1), with K_D non-dimensionalized by u_r and \tau_p by the v/u_r^2. The
friction velocity can be found for a turbulent boundary-layer using a power-law fit for skin
friction; one potential difficulty, however, lies in calculating the correct x, to account for
the leading edge of the plate. This problem is overcome by determining the boundary-
layer thickness, \delta, beyond which the mean velocity profile does not change. Assuming that
the laminar region is short, \delta equals (Potter and Foss, 1982):

$$\delta = 0.38 \left( \frac{v}{U} \right)^{0.2} x^{0.8}$$  \hspace{1cm} (5.14)

for Re_x<10^7. Once x is known, the local skin-friction coefficient, C_f, can now be found
(Potter and Foss, 1982):

$$C_f = \frac{0.059}{Re^{0.2}_x}$$  \hspace{1cm} (5.15)

C_f may be defined in terms of the wall-shear stress, \tau_w, or the friction velocity, u_r:
This yields a direct expression for $u_\tau$:

$$u_\tau = \frac{0.172U}{Re_x^{0.1}}$$  \hspace{1cm} (5.17)

In practice, $\delta$ was too thin to be measured by the current PDPA configuration at the lowest velocity studied ($U \approx 4\text{m/s}$) and equation 5.17 was used to calculate $u_\tau$ to sufficient accuracy, as $u_\tau$ is a very weak function of $x$.

Figure 5.7 plots the dimensionless turbulent boundary layer deposition rates versus $\tau_+$ for $x=38$ and 72 downstream of the leading edge. The curve represents the turbulent deposition correlation by McCoy and Hanratty (1977), and can be viewed in the context of other turbulent deposition data in Figure 5.1. The LIF system measures dimensionless deposition rates that are within the scatter of the data of Figure 5.1. Most significantly, this validates the ability of the LIF system to reliably measure aerosol deposition.

### 5.8 The T-Step Flow: PDPA Particle Statistics Measurements

The PDPA measures mean and fluctuating velocity, number density and Sauter mean diameter vertical profiles at three fixed speeds equal to approximately 4, 8 and 12m/s for all three step heights. The speeds represent the freestream tunnel velocity before the T-step and are termed the reference velocity, $U_r$, where the reference position identifies a position at $x=15.2\text{cm}$ before the step, $y$ equal to the top edge of the step, and $z$ at the spanwise cen-
terline of the test section. The 15° angle of the laser beams relative to the horizontal posed a practical problem in making many measurements, as only y-positions greater than approximately 3.0cm could be accessed by the PDPA optics. As a result, the most detailed flow measurements were obtained for the 2.54cm step flows, where the PDPA could operate at a height just above $h_s$; similarly, the $h_s=1.27$cm and particularly the $h_s=0.64$cm are lacking measurements near the edges of the recirculation and the reattaching flow regions.

5.8.1 Mean Velocity Profiles

Figure 5.8a displays the streamwise evolution of the vertical profile of $U/U_r$ for $h_s=2.54$cm and $U_r=4.15$m/s. As the flow passes over the step, it accelerates to adjust to the smaller tunnel cross-section created by the step and the recirculation region (i.e. at $x=15.2$cm, $x/x_r=0.5$). Note that the velocity measurements begin at approximately $h=6$cm. This reflects a dearth of particles in the recirculation zone for making particle velocity measurements. Further downstream, $U$ decreases as the virtually stagnant (relative to the mean flow rate) secondary flow disappears, providing a greater effective tunnel cross-section for the air to flow through. At $x/x_r=2$ ($x=61$cm), the greatest $U$ is only 20% greater than the freestream reference velocity. Increasing $U_r$ (Figures 5.8b and c) lengthens the reattachment length, causing the location of maximum velocity increase to occur correspondingly further downstream. In addition, at higher $U_r$ the particles take longer to readjust to the slowing flow after reattachment due to their inertia; this is reflected by the larger values of $U/U_r$ at $x=45.7$ and 61cm.

Decreasing the step height reduces the flow blockage of the step and thus reduces the acceleration of the fluid flow around the step. Figures 5.9a, b, and c plot $U/U_r$ vs. $h$ for $h_s=1.27$cm at $U_r=3.88$, 8.15, and 12.27m/s respectively. The particles and the fluid accel-
erate around the step but to a lesser degree than with $h_s=2.54\text{cm}$, while the post-reattachment particle lag still increases with $U_r$. Figures 5.10a, b and c demonstrate that the $h_s=0.64\text{cm}$ minimally accelerates the particles and the fluid around the step. Unfortunately, they also do not capture much, if indeed any, of the strong mean velocity gradient above the recirculation zone, pointing out the inability of the present PDPA configuration to measure in or near the $h_s=0.64\text{cm}$ secondary flow.

5.8.2 Fluctuating Velocity Profiles: $u'$

Figures 5.11a, b, and c show $u'$ profiles as a function of streamwise location for $h_s=2.54$ for $U_r=4.15$, 7.56, and 11.55m/s. The three plots are quite similar in shape, with smoother profiles occurring at higher velocities, and show evidence of vigorous streamwise turbulence. Castro and Haque (1987) provide extensive pulse-wire anemometry measurements of the three fluctuating velocity components in the recirculation bubble, and find that all substantially exceed those expected in a plane mixing layer (PML). Ruderich and Fernholz (1986) present $u'$ and $v'$ data before and after flow reattachment which reveal similar trends for the recirculation region, although their fluctuating quantities exceed those measured by Castro and Haque (1987). The turbulence intensities of Figures 5.11a, b and c above the circulation approach but do not achieve the $x/x_r=0.5$ maxima of $u'/U_r=0.3$ reported by Castro and Haque, presumably because the PDPA could not make measurements sufficiently close to the wall. The measured streamwise turbulent intensities at $x/x_r=1$ agree very well with the value of $\sim 0.25$ obtained by Castro and Haque.

After reattachment, Ruderich and Fernholz (1986) determined that $u'$ decays rather quickly, from $u'/U_r(x/x_r=1)=0.3$ to $u'/U_r(x/x_r=2)=0.2$, approaching the PML value of $u'/U_r=0.17$. The post-reattachment PDPA measurements of $u'/U_r$ agree with these results. On
the other hand, it is the vertical fluctuating component of velocity, $v'$, that controls turbulent deposition. Ruderich and Fernholz find that after reattachment, $v'$ decays only slightly, from $v'/U_r=0.18$ to 0.15. Perhaps not coincidentally, $v'/U_r$ tends toward 0.16 in a plane mixing layer. Taken in the context of $u'/U_r$, which also converges towards the PML value, it appears that the post-reattachment flow, at least in the region under investigation, bears some resemblance to a PML and will termed a quasi-plane mixing layer, or QPML.

The $h_s=1.27\,\text{cm}$ profiles, Figures 5.12a, b and c, are also consistent with one another and come close to achieving the streamwise PML turbulence in the post-recirculation zone region. The $h_s=0.64\,\text{cm}$ $u'/U_r$ profiles (Figures 5.13a, b, and c) appear truncated and never approach 0.15. Undoubtedly, this is due to the minimum vertical height measurement limit of the PDPA (as presently configured).

In all experiments performed, $v'$ for both the quasi-plane mixing layer and the recirculation zone exceeded the gravitational settling velocity, $V_s$, of the particles being investigated by a factor of not less than 4.8, and typically by factor on the order of 10. This implies that it is likely that gravitational settling has a minor effect upon particle deposition relative to turbulent particle dispersion.

5.8.3 Particle Number Density Profiles

Particle $N_D$ profiles are crucial to understanding the physics of particle deposition. The deposition velocity, $K_D$, is normalized to $N_D$, and therefore local increases or decreases in $N_D$ can have a profound influence upon deposition rates. This effect is particularly relevant in unsteady flows. For example, Rudoff et al. (1989) measured local number densities in a swirl stabilized burner using a PDPA and found that $N_D$ could vary by an order of magnitude or more in a period of only a few milliseconds. They ascribe the large fluctua-
tions to the unsteadiness of the flow field and resulting clustering. It is quite possible that the energetic velocity fluctuations in both the secondary flow and the post-reattachment zone will have a similar concentrating effect. In addition, the strong streamline curvature occurring at the T-step will tend to deflect the inertial particles up and above the plate, lowering the local $N_D$ near the plate and altering the size distribution.

Figures 5.14a, b, and c show $N_D$ vertical profiles for $h_s=2.54\text{cm}$ normalized by the $N_{D,r}$, the particle number density measured at the aforementioned reference position. After the aerosols have passed over the T-step, $N_D$ profiles over the recirculation region are very depleted at the regions nearest the walls, irrespective of $U_r$. Typically, $N_D$ decreases by almost two orders of magnitude; in all instances, it exceeds an order of magnitude. This estimate of aerosol depletion may in fact be low, as at several streamwise locations, the PDPA lacked sufficient particles to acquire data! Freestream velocity has a very strong impact on the persistence of the near-wall particle depletion. After reattachment, the $U_r=4.15\text{m/s}$ $N_D$ profile has recovered to within almost 50% of the reference value. The higher speed runs, however, remain particle-lean even at $x/x_r=2.0$.

The $h_s=1.27$ profiles, Figures 5.15a, b, and c, provide an explanation as to why the dearth of particles near the wall persists for higher velocity runs. They exhibit strongly depressed $N_D$ over the recirculation region, although less than the $h_s=2.54\text{cm}$ tests at a similar $U_r$, and the $h_s=1.27\text{cm}$ runs “recovered” from the depletion more quickly. The $U=12.27\text{m/s}$ measurements show a marked increase in $N_D$ in the upper regions of the tunnel, a concentration that increases with $x$. This strongly suggests that as the particles are deflected upwards by the flow curvature at the T-step, their inertia causes them to ballistically traverse much of the mean flow and populate the upper reaches of the tunnel. The flux of particles only begins to become apparent in the $N_D$ profiles further downstream, after they have had time to descend from their ballistic trajectory. The $h_s=2.54\text{cm}$ case
represents the extreme case, as the higher blockage creates an even more severe trajectory for the particles, so much so that the aerosols could end up above the greatest height measured; indeed, substantial aerosol impaction on the test section ceiling was observed after higher-speed $h_s=2.54\text{cm}$ runs.

Continuing to reason along these lines, the $h_s=0.64\text{cm}$ tests should exhibit less $N_D$ depletion and less concentration of particles in the upper vertical planes than either the $h_s=2.54$ or $1.27\text{cm}$ tests because the deflection of the flow around the $h_s=0.64\text{cm}$ is relatively small. This is precisely what occurs. Figures 5.16a, b, and c show that the $N_D$ profile is relatively quite flat for all speeds studied and that the lower-region particle depletion is not nearly as severe as for the larger step heights. However, one caveat does remain: the $N_D$ profiles for the $h_s=0.64\text{cm}$ runs could not be measured near the regions bounding the recirculation region and the QPML because of the minimum measurement height of the PDPA and probably do not accurately reflect the local $N_D$ in these regions. However, I would still expect that, due to the decreased streamline curvature, that the $N_D$ depletion for $h_s=0.64\text{cm}$ tests would not be as severe as for the $h_s=1.27$ and $2.54\text{cm}$ conditions at the same $U_r$.

Of interest is the influence of gravitational settling upon the $N_D$ profiles. If gravity did play an important role in the downward migration of particles towards the wall, I would expect to observe a descent distance of a given portion of the $N_D$ profile equal to the particle’s settling velocity, $V_s$, times the time between measuring stations, i.e. $\Delta x/U$. For the greatest $V_s$ (based on $d_{32}$) encountered in a low-speed run, $V_s$ is of the order of $11\text{cm/s}$, which leads to a maximum settling distance of approximately $0.4\text{cm}$ between measuring stations for $h_s=2.54\text{cm}$ at $U_r=4.14\text{m/s}$. This is much less than the profound deflection of both the aerosols and the flow caused by the T-step, buttressing the argument that gravita-
tional settling of the mean particle flow has little effect upon particle deposition in the
proximity of the T-step. The $N_D$ profiles support this argument.

5.8.4 Sauter Mean Diameter Vertical Profiles

Ideally, deposition experiments should be performed with monodisperse particles to
isolate the effect of particle timescale from that of flow timescale. The array generator,
although representing an improvement upon the spinning disk in producing a relatively
high volume flow rate of aerosol that in practice approaches monodisperse, still produces
over a range of size. Vertical Sauter mean diameter profiles will help to assess if the non-
uniformity of the spray has a significant affect upon particle deposition rate. For example a
concentration of small particles in a specific region implies that the particles would be
more likely to follow a flow structure, which could either decrease deposition (see Figure
5.1) or increase deposition e.g. by being entrained in a slow-moving secondary flow.

Figures 5.17a, b, and c depict Sauter mean diameter measurements normalized to $d_{32}$
at the reference location for $h_s=2.54\text{cm}$. At higher $U_r$, the trend is for larger, more inertial
particles to inhabit the regions over the recirculation region and at reattachment. In these
regions, there exists a dearth of particles, and it is predominantly the larger particles that
manage to pass through there. Presumably, the larger particles are relatively overrepre-
sented because they have the inertia to overcome the strong flow curvature forces about
the T-step and ballistically pass through the flow streamlines to enter the areas bounding
the recirculation zone. Put another way, the particle possesses sufficient inertia such that
their behavior is no longer dictated by their interactions with the flow, but instead by their
history, i.e. their past trajectory. Further downstream, $d_{32}$ approaches $d_{32r}$, the reference
value taken from PDPA measurements 15.2cm before the T-Step.
The $h_s=1.27\text{cm}$ tests, shown in Figures 5.18a, b, and c, support this trend, albeit to a lesser extent. The $U_r=3.88\text{m/s}$ region where $d_{32}/d_{32r}$ is maximized is a region of low $N_D$ ($N_D/N_{Dr}<0.08$), as is the $U_r=8.15\text{m/s}$ test's "near-wall" maxima ($N_D/N_{Dr}<0.10$ at $x/x_r=0.5$). However, the high speed run defies this trend, as the larger particles do not congregate in regions of lower $N_D$. The inability of the PDPA to interrogate closer to the wall in the $h_s=0.64\text{cm}$ tests (Figures 5.19a, b, and c) prevents meaningful interpretation, only speculation, about the concentration of more inertial aerosols near to the wall.

The concentration of larger particles above the recirculation zone would tend to reduce their probability of being entrained in the secondary flow, while increasing the chance for particle deposition by gravitational sedimentation. The net effect upon deposition rates is not clear.

### 5.9 Secondary Flow Deposition Results

Initially, I will present the deposition data as a function of step height and the reference freestream velocity, $U_r$. This section provides an overview of the basic secondary flow and reattachment region deposition results and illuminates several overall trends. However, it neglects the basic physics of the particle-flow interaction. Furthermore, $K_D$ is calculated in this section using the reference $N_D$, in an attempt to predict particle deposition rates based solely on a easily obtainable mean flow quantity. The next section examines the effect of particle dispersion upon particle deposition to explain more completely the depositing results presented in this section.
Deposition rates are measured behind the three T-steps at $U_r$ ranging from 3.3 to 13 m/s; the PDPA measured $U_r$, for all experiments, at $x$ located 15.3 cm before the step, at $y$ found at the top edge of the step, and at $z$ equal to the transverse centerline of the test section. Figure 5.20 presents dimensionless deposition rate versus normalized streamwise location for all of the $h_s=0.64$ cm runs for $U_r=3.66-12.20$ m/s; note that the lines do represent actual data and not theory. A prominent result is that $K_D$ is globally depressed in the recirculation region relative to the post-reattachment zone and that this result is more pronounced for the lower velocity experiments. However, there does not appear to be a distinct change in the deposition rate at $x=x_r$; instead, $K_D$ consistently increases monotonically with $x$. In the recirculation zone, the data also seem to reduce to a common range of values when $K_D$ is scaled with $U_r$. Deposition rates downstream of reattachment do not collapse with $U_r$. Instead, the $K_D/U_r$ data “band” with $U_r$, with higher $U_r$ experiments lying below those of lower $U_r$. This sorting based on $U_r$ becomes more distinct at locations successively further downstream.

Much of the data scatter seen within the recirculation zone may be due to the low levels of deposition. If the deposited fluorescein film is thin enough, the output signal, VPMT, will approach that of the ambient light and the reflected laser light, making precise quantification of the deposition rate very difficult. Deposition measurements naturally have quite a bit of scatter to them, which can be smoothed out with longer and longer runs. The very low deposition rates encountered in the secondary flow increase the spatial variance of deposition, as an individual deposition event, i.e. an individual particle, can locally dominate the measured signal. Thus, much of the data scatter in the recirculation region
most likely reflects both the background noise of the LIF technique and also the relatively small number of deposition events that occur in the recirculation zone.

Figure 5.21 displays a summary of the \( h_s=1.27\text{cm} \) runs, again encompassing a range of \( U_r \). When compared to the \( h_s=0.64\text{cm} \) experiments, the same trends are observed: lower deposition rates in the recirculation zone (more prominent at lower \( U_r \)), the tendency of the data to collapse with \( U_r \) in the recirculation region, and the “banding” with \( U_r \). However, the deposition rate before reattachment in the \( h_s=1.27\text{cm} \) experiments is almost an order of magnitude less than those typically found in the \( h_s=0.64\text{cm} \) tests. Figure 5.22 shows how deposition rates vary with downstream location for the \( h_s=2.54\text{cm} \) tests. The banding of \( K_D/U \) with \( U_r \) is even more pronounced in this instance, but the data do not collapse as well for \( x/x_r<1 \).

In sum, dimensionless deposition rates in the recirculation zone are much less than those found after reattachment, a trend that is accentuated for low \( U_r \) and larger \( h_s \). \( K_D \) appears to scale reasonably well in the recirculation region with \( U_r \) and “banding” of \( K_D/U \) with \( U_r \) exists, particularly downstream of reattachment. The persistence of velocity “banding” demands an explanation and will be examined in detail in Section 5.10.

5.9.2 A Global view of Deposition: By Reference Velocity

The presence of data “banding” with \( U_r \) suggests plotting runs with similar \( U_r \) together to observe if the data collapses for the three step heights. Figure 5.23 presents several runs for which \( U_r=4\text{m/s} \). The data all show an increase of at least an order of magnitude in \( K_D/U \) from the secondary flow region into the reattached flow and collapse rather well irrespective of \( h_s \). At higher \( U_r \), the data change drastically. For example, for \( U_r=8\text{m/s} \) (Figure 5.24) the increase in \( K_D/U \) is much less marked than for \( U_r=4\text{m/s} \) and \( K_D/U \) begins to
band with h_s, with K_D/U generally greater for smaller h_s. The U_r~12m/s runs of Figure 5.25 are even flatter than the U_r~8m/s experiments and exhibit stronger banding with h_s; quite clearly, as h_s increases, K_D/U decreases.

The fact that the deposition data do not collapse to a single trend based on either h_s or U_r reflects the complexity of the deposition process. The plots presented above do not take into account the mechanism of particle motion to the wall, the flow field, nor the interaction of the particle with the turbulent and secondary flows of the geometry, i.e. the Stokes number of the particles relative to the flow. Thus, to gain an understanding of the spatial distribution of deposition behind the T-step, the behavior of the particles in the flow needs to be measured, understood, and applied to model the deposition process. The recirculation region and the flow downstream of reattachment will be studied individually, as the fluid dynamics of the two regions are quite distinct from each other.

5.10 The Scaling of Deposition in the Recirculation Region

5.10.1 Eddy Turnover Timescale

Clearly, aerosol deposition rates are lower in the recirculation region behind the T-step and vary strongly as a function of x/x_r, h_s, and U. However, it is possible that the deposition rates measured in the secondary flow may collapse if an appropriate flow time scale, \( \tau_f \), can be found to scale the data. The eddy turnover time, \( \tau_r \), is prominent in velocity autocorrelations taken by Castro and Haque in the recirculation zone (1987), and represents an obvious choice for \( \tau_f \) in the recirculation region:
Turbulent deposition data (e.g. Griffith, 1990) is usually presented as a dimensionless plot of $\tau_p/\tau_f$ vs. $K_D/U$. Similarly, scaling with $\tau_r$ suggests a plot of $\tau_p/\tau_r$ versus $K_D/U$. Figures 5.26a and b show the secondary flow deposition rate at $x/x_r=0.5$ and 1.0, normalized by recirculation parameters. The data at $x/x_r=0.5$ is spread over two orders of magnitude and generally flat, while the $x/x_r=1.0$ plot represents a modest improvement over the $x/ x_r=0.5$ data. It also shows that $K_D/U$ scatters about a value of the order of 0.001. Taken in the context of past turbulent deposition data, i.e. Figure 5.1, the deposition rates in the reattachment zone are almost two orders of magnitude less than in a turbulent flow. The low deposition rates inside the recirculation zone may be responsible for much of the scatter of the data, especially at $x/x_r=0.5$. It is not clear that $\tau_r$ is or is not the appropriate time scale for particle deposition behind a T-step.

5.10.2 Turbulent Timescale

Measurements of turbulent quantities by Castro and Haque (1987) indicate that the recirculation zone is home to vigorous turbulent fluctuations; for example, $\nu'=0.24U$ at $x/ x_r=0.5$ and 1.0. Therefore, another option is to scale the deposition data with the local turbulence in the recirculation zone, specifically the component of velocity which provides a measure of turbulent motion to (and also away from) the wall, $\nu'$. The turbulent timescale, $\tau_t$, can be expressed as:

$$\tau_t = \frac{\nu}{\nu'^2} \quad (5.19)$$
and $K_D$ is non-dimensionalized by $v'$, the rms flow velocity. Figures 5.27a and b display the secondary flow deposition data normalized by the proposed turbulent scales at $x/x_r=0.5$ and 1.0. The data, which include several different freestream velocities and all three $h_s$ studied, suggest that $K_D/v'$ is approximately independent of $\tau_p/\tau_t$, but varies with position in the secondary flow despite the fact that both locations studied have the same $\tau_t$. This implies that the distribution of the particles in the secondary flow, i.e. the spatial distribution of aerosol $N_D$, plays a powerful role in determining $K_D$.

The recirculation zone deposition velocities are now calculated using the $N_D$ measured nearest the wall instead of the reference value initially employed. Figure 5.28a plots the adjusted $K_D/v'$ versus $\tau_+$ for $x/x_r=0.5$. The data does not appear to have converged substantially better despite the $N_D$ correction, and the magnitude of $K_D/v'$ still remains approximately an order of magnitude less than that expected for a turbulent flow (i.e. Figure 5.1). Figure 5.28b reflects the $N_D$ correction for $K_D$ at $x/x_r=1.0$. Here, the deposition data does appear to show greater convergence and now lies an order of magnitude less than the expected value of $K_D/v'$ for the turbulent deposition of inertial particle.

There are several reasons why the $N_D$ correction is not entirely successful in properly scaling the secondary flow deposition. First, as mentioned earlier, the deposition rates in the secondary flow tended to be quite low, resulting in a low signal-to-noise ratio. This is more relevant at locations closer to the step, e.g. at $x/x_r=0.5$. Second, the $N_D$ measurements themselves do not actually measure the $N_D$ in the bulk of the secondary flow region, let alone at the bottom of the recirculation zone where the particles deposit. Therefore, the $N_D$ measurements probably do not represent the local $N_D$ at the sight of deposition, although they may be somewhat close for the $h_s=2.54$cm tests. In this regard, the $h_s=0.64$cm $N_D$ corrections are in all probability too low (i.e. $N_D$ too high) and that data should be given little credibility in an $N_D$-correction context.
The deposition data do not clearly scale with either the turbulent nor the eddy turnover timescale in the recirculation region, sharing moderate agreement with both scales, particularly at higher $St_k$. Both models do indicate that the deposition rates of inertial aerosols in the secondary flow are at least an order of magnitude lower than those found in a turbulent boundary layer (see Figure 5.1).

5.11 Scaling of Deposition in the Region Downstream of Recirculation

The experiments presented earlier (e.g. Figures 5.20-5.25) indicate that $K_D$ is greater downstream of reattachment than in the recirculation zone, particularly at lower $U_r$. Earlier, in the discussion of the fluctuating velocity profiles, it was noted that the post-reattachment resembles, in several aspects, a plane mixing layer, PML; specifically, $v'$ remained almost constant after the flow reattachment. Therefore, this suggests scaling aerosol deposition in the post-recirculation region with plane mixing layer turbulence quantities, specifically with the reported values of $v'$. Castro and Haque (1987) report that $v'/U_r \approx 0.16$ in a PML, and Figures 5.29a, b, and c display plots of $\tau_{f}/\tau_{i}$ versus $K_D/v'$ (using $v'/U_r=0.16$) for $x/x_r=1.25$, 1.75, and 2.0 respectively. For each streamwise location, the local deposition rate is highest at smaller values of $\tau_+$ and then ramps down to an approximately constant value of $K_D/v' \approx 0.001-0.01$ for $\tau_+ > 1,000$. However, the peak value of $K_D/v'$ increases at stations further downstream. Dimensionless deposition rate at $x/x_r=1.75$ and 2.0 peaks around 0.25, whereas at $x/x_r=1.25$, it peaks at $\approx 0.05$ despite the presence of more vigorous turbulent fluctuations at $x/x_r=1.25$ than at $x/x_r=1.75$ or 2.0!

The $N_D$ profiles presented in Section 5.9.3 help to explain the apparent decrease in deposition rate at larger values of $\tau_+$. The $N_D$ profiles showed a dramatic decrease in $N_D$
in the post-reattachment region, which is not reflected in the deposition rates depicted in Figures 5.29a-c. Figures 5.30a-d take into account the depletion of particles near the wall, using instead the local ND measurement closest to the wall. For \(x/x_t=1.25, 1.5, 1.75, \) and 2.0. At \(x/x_t=1.25\), the ND-corrected data still exhibits a significant degree of scatter, with the \(h_s=0.64\) cm points lying consistently below most of the other data; this most likely results from the inability of the present PDPA configuration to make ND measurements nearer to the wall. However, further downstream the data begin to converge until at \(x/x_t\) they cluster around \(K_D/v'=0.1\). Interestingly, further downstream the \(h_s=0.64\) cm runs also start to approach the magnitude of the other data, particularly at the lower speed runs. This happens because the mixing layer thickens with \(x\), causing the ratios of \(N_D/N_{Dr}\) to approach one another.

The agreement of the ND-corrected \(h_s=2.54\) cm runs with turbulent deposition theory at all four \(x/x_t\) locations investigated is consistent with the idea that the post-reattachment zone deposition rate scales as would turbulent deposition in a plane mixing layer. The \(h_s=2.54\) tests reflect ND measurements closest to the flow from which the particles deposit, thus lending the most credibility to these measurements and the resulting values of \(K_D\). The fact that many values of \(K_D/v'\) lie below the inertial aerosol turbulent deposition correlation value of \(K_D/v'=0.1\) has been observed before and is not particularly troubling. For example, Lee et al. (1989) injected particles with \(40<\tau_+<3,000\) at the centerline of a vertically downward turbulent pipe flow and measured the deposition rate using the dye-washing technique. They noticed a decrease in \(K_D/u_t\) for \(\tau_+>500\) and attribute the decrease to the relative inability of the particles to follow the turbulent fluctuations that impart momentum to the particles in the direction of the wall.

Clearly, the post-reattachment \(H=2.54\) cm deposition results collapse well with the turbulent scaling because of the relative accuracy of the local ND measurements. Figures
31a-d display particle deposition rates for all three step heights using the $h_s=2.54\text{cm}$ local $N_D$ values for also the $h_s=1.27\text{cm}$ and $0.64\text{cm}$ steps. Using this scaling, the deposition data now lie even closer to the data of Figure 5.1. In fact, many of the $h_s=0.64$ and $1.27$ data now come close to overshooting Figure 5.1, most likely because the flow around $h_s=2.54\text{cm}$ T-step is not identical to the other two cases. Specifically, the streamline curvature caused the $h_s=2.54\text{cm}$ T-step is more severe and is shown to deflect the particles further away from the deposition surfaces than the other two step heights. This implies that the "near wall" $N_D$ of the $h_s=2.54\text{cm}$ step would tend to be lower than the other heights. Thus, when the $h_s=2.54\text{cm}$ $N_D$ values are applied to the two smaller step heights, it would create higher overall $K_D/v'$ values at these heights - which is, generally speaking, precisely what occurs in Figures 30a-d. Above all, this emphasizes the importance of knowing the details of the local aerosol $N_D$ to obtain a deposition rate; bulk $N_D$ measurements by themselves are not sufficient.

One difficulty with obtaining more precise agreement with turbulent deposition theory is that $v'$ is never measured; it is calculated by measuring $U$. A second concern is that $v'$, which is calculated for the flow, may not represent the vertical fluctuating velocity of the particle. Rogers and Eaton (1990) studied the velocity behavior of glass beads in a vertical, turbulent boundary-layer and discovered that $v'$ of relatively large particles, i.e. $d_p=50$ and $90\text{mm}$ was strongly attenuated in the direction normal to the wall. If this were the case, then $K_D/v'$ would tend to increase in magnitude (a correction that would improve the agreement of the data with past turbulent deposition results), while $\tau_+$ decreased. Finally, the deposition rates are obtained from one-hour long tests. A test of the spatial variance of deposition rate reported in Section 3.10 (for a flow similar to a turbulent boundary layer) indicates that one-hour experiments have an RMS variation of almost 50% of the mean.
suggesting that a substantial portion of the deposition data scatter results from spatial inhomogeneity of the deposition rate.

5.12 Conclusions

The aerosol deposition experiments contain several important findings. First, LIF deposition measurements in a turbulent boundary layer agree well with prior turbulent boundary layer deposition results and confirm the validity of LIF deposition measurements. Deposition of inertial aerosols in the recirculation zone is strongly depressed relative to the post-recirculation quasi-plane mixing layer region and a flat plate boundary layer. Particle number density profile measurements indicate that the low secondary flow deposition rates occur because the particles possess too much inertia to successfully negotiate the streamline curvature at the T-step and become entrained in the secondary flow, i.e. there is a dearth of particles in the region bounding the secondary flow structure. It is not clear whether secondary flow deposition behind a T-step scales better with recirculation or turbulent parameter.

Deposition rates in the post-reattachment region, i.e. a quasi-plane mixing layer, scales quite well with the local fluctuating velocity normal to the wall, \( v' \). Local number density measurements relatively near the wall are also significantly lower than bulk flow number density, leading to lower rates than predicted by turbulent deposition results. However, when the deposition rate is scaled with the local number density, the adjusted post-reattachment data converges to the order of the turbulent deposition data.

As a result, the deposition rates of inertial aerosols in a secondary flow or the turbulent region afterwards cannot be gleaned from global number density measurements. They can
only be accurately predicted with the knowledge of the local number density in the region of interest.

Gravity appears to have a negligible effect upon particle deposition rates relative to the flow in the recirculation region and also in the post-reattachment zone studied. This is true in both a local and bulk sense. Locally, the turbulent fluctuations generally exceed the settling velocity of the aerosols by a factor greater than five. On a larger scale, the strong streamline curvature at the T-step deflects the aerosols a much greater distance than they potentially could settle due to gravity in the streamwise distances under consideration.

The results of the deposition experiments can be interpreted and applied to estimate the deposition of inertial particles behind a flow obstruction. They suggest that if the blockage presents appreciable flow blockage, i.e. it is not merely a surface roughness element and creates bulk flow streamline curvature, deposition in the secondary flow region will be very low, at least two orders of magnitude lower than in a plane turbulent boundary layer. Similarly, deposition rates in the region immediately beyond flow reattachment will also be lower than for a turbulent boundary layer, but higher than in the particle-lean recirculation zone. A reliable estimate of the local deposition rate can only be obtained by knowing the local number density and applying conventional turbulent deposition correlations. However, if the obstruction presents sufficient flow blockage to powerfully deflects the mean flow, i.e. as with the T-step experiments, the highest deposition rates will probably occur on the wall opposite the obstruction due to inertial impaction of the particles deflected by the flow. This deposition rate could be estimated by finding the local component of velocity of the flow normal to the step as it passes over the step at a specific vertical position, assuming that the particle inherits this velocity, and then calculating the stop distance of the particle and seeing if the particle intercepts the top wall. For more inertial particles, the opposite wall boundary layer would probably have little effect upon particle
deposition due to the ballistic nature of the particles. The effect of gravity, if relevant to
the motion of the particle, can be accounted for by adding (or subtracting) the settling
velocity during the trajectory of the particle (assuming no interaction of gravity and turbu-
 lent-inertia effects).
Figure 5.1: Deposition Rates for Droplets in a Turbulent Flow; (McCoy et al., 1977, Lopes, 1986, taken from Griffith, 1990).
Figure 5.2: Eddy Deposition Rates of Particles on Smooth Surfaces; (from Im and Ahluwalia, 1989).
Figure 5.3: Diagram of the T-Step Tunnel Geometry.
Figure 5.4: Three-Dimensional View of T-Step Secondary Flow; (from Ruderich and Fernholz, 1986).
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Figure 5.5a: Surface Flow Visualization Behind the T-Step, $h_s=1.27\text{cm}$, $U=12.65\text{m/s}$.
Figure 5.5b: Surface Flow Visualization Behind the T-Step.
$h_s=2.54\text{cm}, U=9.70\text{m/s}.$
Figure 5.5c: Surface Flow Visualization Behind the T-Step (Reattachment Zone)

$h_S = 1.27 \text{cm}, U = 12.65 \text{m.s.}$
Figure 5.5d: Surface Flow Visualization Behind the T-Step, $h_s=2.54\, \text{cm}$, $U=3.5\, \text{m.s.}$
Figure 5.6a: Deposition Rate Data Uncorrected for Change in Fluorescein Concentration, \( h_s = 2.54 \text{cm}. \)
Figure 5.6b: Deposition Rate Data Corrected for Change in Fluorescein Concentration.
Figure 5.7: LIF Particle Deposition Rates in a Turbulent Boundary Layer, $K_d/U$ versus $\tau_+$. 

Mc&H (1977)
Vertical Variation of $U/U_{ref}$ versus $X$
for $H=2.54\,\text{cm}$, $U_{ref}=4.15\,\text{m/s}$

![Graph showing vertical variation of $U/U_{ref}$ versus $X$.]

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**Figure 5.8a:** T-Step Mean Velocity Profiles, $U/U_{r}$ versus $y$,
$h_s=2.54\,\text{cm}$, $U_{r}=4.15\,\text{m/s}$. 
Figure 5.8b: T-Step Mean Velocity Profiles, U/U_{ref} versus y, 
\( h_s = 2.54 \text{cm}, U_{ref} = 7.54 \text{m/s} \).
Vertical Variation of $U/U_{ref}$ versus $X$
for $H=2.54\text{cm}$, $U_{ref}=11.55\text{m/s}$

Figure 5.8c: T-Step Mean Velocity Profiles, $U/U_r$ versus $y$,
h_s=2.64\text{cm}$, $U_r=11.55\text{m/s}$.
Vertical Variation of $U/U_{ref}$ versus $X$
for $H=1.27\text{cm}$, $U_{ref}=3.88\text{m/s}$

Figure 5.9a: T-Step Mean Velocity Profiles: $U/U_r$ versus $y$,
h$_s=1.27\text{cm}$, $U_r=3.88\text{m/s}$.
Vertical Variation of $U/U_{ref}$ versus $X$
for $H=1.27\text{cm}$, $U_{ref}=8.15\text{m/s}$

Figure 5.9b: T-Step Mean Velocity Profiles: $U/U_r$ versus $y$,
h_s=1.27\text{cm}, U_r=8.15\text{m/s}.
Vertical Variation of $U/U_{ref}$ versus $X$
for $H=1.27\text{cm}$, $U_{ref}=12.27\text{m/s}$

Figure 5.9c: T-Step Mean Velocity Profiles: $U/U_r$ versus $y$,
$h_s=1.27\text{cm}$, $U_r=12.27\text{m/s}$. 
Figure 5.10a: T-Step Mean Velocity Profiles: $U/U_r$ versus $y$,
$h_s=0.64$, $U_r=3.92\text{m/s}$.
Vertical Variation of $U/U_{ref}$ versus $X$
for $H=0.64\text{cm}$, $U_{ref}=8.32\text{m/s}$

Figure 5.10b: T-Step Mean Velocity Profiles: $U/U_r$ versus $y$,
$h_s=0.64\text{cm}$, $U_r=8.32\text{m/s}$. 
Figure 5.10c: T-Step Mean Velocity Profiles: $U/U_r$ versus $y$, $h_s=0.64\text{cm}$, $U_r=12.63\text{m/s}$.
Figure 5.11a: T-Step Fluctuating Velocity Profiles, $u'/U_r$ versus $y$,
$h_s=2.54\text{cm}, U_r=4.15\text{m/s}$. 

Vertical Variation of $u'/U_r$ versus $X$
$U=4.15\text{m/s}, H=2.54\text{cm}$. 

- $X=-3.2\text{cm}$
- $X=15.2\text{cm}$
- $X=30.5\text{cm}$
- $45.7\text{cm}$
- $X=61.0^\prime$
Figure 5.11b: T-Step Fluctuating Velocity Profiles, $u'/U_r$ versus $y$, $h_s=2.54\text{cm}$, $U_r=7.54\text{m/s}$.
Figure 5.11c: T-Step Fluctuating Velocity Profiles, $u'/U_r$ versus $y$, $h_s=2.54\text{cm}$, $U_r=11.55\text{m/s}$.
Figure 5.12a: T-Step Fluctuating Velocity Profiles, $u'/U_r$ versus $y$, $h_s=1.27\text{cm}$, $U_r=3.88\text{m/s}$.
Vertical Variation of $u'/U_r$ versus $X$

$U=8.15\text{m/s}, H=1.27\text{cm}$.

Figure 5.12b: T-Step Fluctuating Velocity Profiles, $u'/U_r$ versus $y$, $h_s=1.27\text{cm}, U_r=8.15\text{m/s}$.
Vertical Variation of $u'/U_r$ versus $X$
for $H=1.27\text{cm}; \ U=12.27\text{m/s}$.

Figure 5.12c: T-Step Fluctuating Velocity Profiles, $u'/U_r$ versus $y$,
h$_s=1.27\text{cm}, \ U_r=12.27\text{m/s}$. 

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Figure 5.13a: T-Step Fluctuating Velocity Profiles, $u'/U_r$ versus $y$, $h_s=0.64\text{cm}$, $U_r=3.92$. 
Vertical Variation of $u'/U_r$ versus $X$
$U=8.32\,\text{m/s}, \, H=0.64\,\text{cm}$.

Figure 5.13b: T-Step Fluctuating Velocity Profiles, $u'/U_r$ versus $y$,
$h_s=0.64\,\text{cm}, \, U_r=8.32\,\text{m/s}$. 
Vertical Variation of $u'/U_r$ versus $X$

$U=12.63\text{m/s}, H=0.64\text{cm}$.

Figure 5.13c: T-Step Fluctuating Velocity Profiles, $u'/U_r$ versus $y$,

$h_s=0.64\text{cm}, U_r=12.63\text{m/s}$.
Figure 5.14a: T-Step Number Density Profiles, $N_d/N_{d_r}$ versus $y$, $h_s=2.54\text{cm}$, $U_r=4.15\text{m/s}$. 

Vertical Variation of $N_d$ versus $X$ for $H=2.54\text{cm}$, $U_{ref}=4.15\text{m/s}$
Vertical Variation of Nd versus X  
for H=2.54cm, Uref=7.54m/s

Figure 5.14b: T-Step Number Density Profiles, Nd/Nd_r versus y,  
h_s=2.54cm, U_r=7.54m/s.
Figure 5.14c: T-Step Number Density Profiles, \( N_D/N_Dr \) versus \( y \), \( h_s=2.54\text{cm}, U_r=11.55\text{m/s} \).
Vertical Variation of Nd versus X  
for H=0.5", Uref=3.88m/s

Figure 5.15a: T-Step Number Density Profiles, \( N_D/N_{Dr} \) versus y,  
\( h_s=1.27\text{cm}, U_r=3.88\text{m/s}. \)
Figure 5.15b: T-Step Number Density Profiles, $\frac{N_D}{N_{Dr}}$ versus $y$, $h_s=1.27\text{cm}$, $U_r=8.15\text{m/s}$.
Figure 5.15c: T-Step Number Density Profiles, $N_d/N_{Dr}$ versus $y$, $h_s=1.27\text{cm}$, $U_r=12.27\text{m/s}$. 
Figure 5.16a: T-Step Number Density Profiles, $N_D/N_{Dr}$ versus $y$, $h_s=0.64\text{cm}$, $U_r=3.92\text{m/s}$.
Vertical Variation of Nd versus X
for \( H=0.64\text{cm} \), \( U_{\text{ref}}=8.32\text{m/s} \)

Figure 5.16b: T-Step Number Density Profiles, \( \frac{N_d}{N_{d,\text{ref}}} \) versus y,
\( h_s=0.64\text{cm}, U_{t}=8.32\text{m/s} \).
Figure 5.16c: T-Step Number Density Profiles, \( \frac{N_d}{N_{d\text{r}}} \) versus \( y \), \( h_s = 0.64\text{cm} \), \( U_r = 12.63\text{m/s} \).
Vertical Variation of D32 versus X for H=2.54cm; 4.15m/s.

Figure 5.17a: T-Step Sauter Mean Diameter Profiles, $d_{32}$ versus $y$, $h_s=2.54cm$, $U_r=4.15m/s$. 
Figure 5.17b: T-Step Sauter Mean Diameter Profiles, d_{32} versus y, 
h_s=2.54cm, U_r=7.54m/s.
Vertical Variation of $D_{32}$ versus $X$
for $H=2.54\text{cm}$; $U=11.55\text{m/s}$.

Figure 5.17c: T-Step Sauter Mean Diameter Profiles, $d_{32}$ versus $y$,
h$_s=2.54\text{cm}$, $U_r=11.55\text{m/s}$. 
Vertical Variation of $D_{32}$ versus $X$
for $H=1.27\,\text{cm}$; $U_r=3.88\,\text{m/s}$.

Figure 5.18a: T-Step Sauter Mean Diameter Profiles, $d_{32}$ versus $y$,
$h_5=1.27\,\text{cm}$, $U_r=3.88\,\text{m/s}$.
Vertical Variation of D32 versus X for H=1.27cm; U=8.15m/s.

Figure 5.18b: T-Step Sauter Mean Diameter Profiles, d_{32} versus y, h_s=1.27cm, U_r=8.15m/s.
Vertical Variation of D32 versus X for H=1.27cm; U=12.27m/s.

Figure 5.18c: T-Step Sauter Mean Diameter Profiles, $d_{32}$ versus y, $h_s=1.27$cm, $U_r=12.27$m/s.
Vertical Variation of D32 versus X for H=0.64cm; U=3.92m/s.

Figure 5.19a: T-Step Sauter Mean Diameter Profiles, d_{32} versus y, h_s=0.64cm, U_r=3.92m/s.
Vertical Variation of $D_{32}$ versus $X$
for $H=0.64\text{cm}; U=8.32\text{m/s}$.

Figure 5.19b: T-Step Sauter Mean Diameter Profiles, $d_{32}$ versus $y$,
h$_s=0.64\text{cm}, U_r=8.32\text{m/s}$.
Vertical Variation of $D_{32}$ versus $X$
for $H=0.64\text{cm}$; $U=12.63\text{m/s}$.

Figure 5.19c: T-Step Sauter Mean Diameter Profiles, $d_{32}$ versus $y$,
h$_s=0.64\text{cm}$, $U_r=12.63\text{m/s}$.
Figure 5.20: T-Step Deposition: $K_d/U$ versus $x/x_r$ Tests, $h_s=0.64$ cm.
Figure 5.21: T-Step Deposition: $K_d/U$ versus $x/x_r$ Tests, $h_s=1.27\text{cm}$. 

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Figure 5.22: T-Step Deposition: $K_D/U$ versus $x/x_r$ Tests, $h_s=2.54$cm.
Figure 5.23: T-Step Deposition: $K_D/U$ versus $x/x_r$ Tests, $U_r \sim 4$ m/s.
Figure 5.24: T-Step Deposition: $K_D/U$ versus $x/x_r$ Tests, $U_r \sim 8\text{ m/s}$. 

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Figure 5.25: T-Step Deposition: $K_D/U$ versus $x/x_r$ Tests, $U_r \sim 12$ m/s.
Recirculation Scaling (Corr. for Cf)

\[ \frac{X}{X_r} = 0.5 \]

Figure 5.26a: Recirculation Zone Deposition, Scaled with the Eddy Turnover Timescale, \( \frac{K_d}{U} \) versus \( \frac{\tau_p}{\tau_r} \), \( \frac{x}{x_r} = 0.5 \).
Recirculation Scaling (Corr)
\[ \frac{X}{X_r} = 1.0 \]

Figure 5.26b: Recirculation Zone Deposition, Scaled with the Eddy Turnover Timescale, \( \frac{K_d}{U} \) versus \( \frac{T_p}{T_r} \), \( \frac{x}{x_r} = 1.0 \).
Figure 5.27a: Recirculation Zone Deposition, Scaled with the Turbulent Timescale, $K_D/v'$ versus $\tau_+, x/x_r=0.5$. 

![Graph showing recirculation zone deposition scaled with the turbulent timescale, $K_D/v'$ versus $\tau_+, x/x_r=0.5$.](image-37x-10-688x802)

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Figure 5.27b: Recirculation Zone Deposition, Scaled with the Turbulent Timescale, $K_D/v'$ versus $\tau_+ = x/x_r = 1.0$. 
Figure 5.28a: Recirculation Zone Deposition Applying Local $N_D$, Scaled with the Turbulent Timescale, $K_D/v'$ versus $\tau_+, x/x_r=0.5$. 
Figure 5.28b: Recirculation Zone Deposition Applying Local N_D, Scaled with the Turbulent Timescale, K_d/v' versus \( \tau_+ \), \( x/x_r = 1.0 \).
Figure 5.29a: Post-Reattachment Deposition, Scaled with the Turbulent Mixing Layer Timescale, $K_d/v'$ versus $\tau_+ \times x/x_r$, $X/X_r = 1.25$. 
Figure 5.29b: Post-Reattachment Deposition, Scaled with the Turbulent Mixing Layer Timescale, $K_D/v'$ versus $\tau_+, x/x_r=1.75$. 
Figure 5.29c: Post-Reattachment Deposition, Scaled with the Turbulent Mixing Layer Timescale, $K_D/v'$ versus $\tau_+ x/x_r=2.0$. 
Figure 5.30a: Post-Reattachment Deposition Applying Local $N_D$, $Sc$; Turbulent Mixing Layer Timescale, $K_D/v'$ versus $t_+$, $x_j$
Figure 5.30b: Post-Reattachment Deposition Applying Local $N_D$, Scaled with the Turbulent Mixing Layer Timescale, $K_D/v'$ versus $\tau_+$, $x/x_r=1.5$. 
Figure 5.30c: Post-Reattachment Deposition Applying Local $N_D$, Scaled with the Turbulent Mixing Layer Timescale, $K_D/v'$ versus $\tau_*, x/x_r=1.75$. 
Figure 5.30d: Post-Reattachment Deposition Applying Local $N_D$, Scaled with the Turbulent Mixing Layer Timescale, $K_D/v'$ versus $\tau_+,$ $x/x_r=2.0.$
Figure 5.31a: Post-Reattachment Deposition Applying Local $N_D$ of $h_s=2.54\text{cm}$ to All Runs, Scaled with the Turbulent Mixing Layer Timescale, $K_D/v'$ versus $\tau_+, x/x_f=1.25$
Figure 5.31b: Post-Reattachment Deposition Applying Local $N_D$ of $h_s=2.54\text{cm}$ to All Runs, Scaled with the Turbulent Mixing Layer Timescale, $K_D/v'$ versus $\tau_+\text{, }x/x_r=1.5$
Figure 5.31c: Post-Reattachment Deposition Applying Local \( N_D \) of \( h_s = 2.54 \text{cm} \) to All Runs, Scaled with the Turbulent Mixing Layer Timescale, \( K_D/\nu' \) versus \( \tau_+ \), \( x/x_r = 1.75 \)
Figure 5.31d: Post-Reattachment Deposition Applying Local $N_D$ of $h_s=2.54\text{cm}$ to All Runs, Scaled with the Turbulent Mixing Layer Timescale, $K_D/\nu'$ versus $\tau_+\times/x_f=2.0$
References


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Appendix A  New Contraction Coordinates

Table A.1 presents the width of the cut-out insert at a given axial position WHEN THE POLYETHYLENE SHEET LIES FLAT.

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<th>Axial Direction, inches</th>
<th>Width, inches</th>
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</tr>
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</tr>
<tr>
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</tr>
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<td>9</td>
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</tr>
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</tr>
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</tr>
<tr>
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</tr>
<tr>
<td>36</td>
<td>40.0+</td>
</tr>
<tr>
<td>48</td>
<td>40.0+</td>
</tr>
</tbody>
</table>

*Table A.1: Modified Contraction Polyethylene Sheet Measurements*

The polyethylene sheets were attached to the styrofoam blocks and mounted in the tunnel. In the tunnel, the spacing between the original tunnel bottom and the top surface of the new contraction, the height of the contraction shape, and the height of the original tunnel bottom were measured at several streamwise locations in the tunnel and are exhibited.
in Table A.2. Note that the streamwise distance is NOT the same as the axial distances referred to in Table A.1 above. The inserts are 24” long.

<table>
<thead>
<tr>
<th>Streamwise Distance from Contraction Mouth, inches</th>
<th>Height of Contraction Shape</th>
<th>Height of Tunnel Bottom, inches</th>
</tr>
</thead>
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<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0.25</td>
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</tr>
<tr>
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<td>0.75</td>
<td>0</td>
</tr>
<tr>
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<tr>
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<td>1.88</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>2.5</td>
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</tr>
<tr>
<td>12</td>
<td>3.25</td>
<td>0</td>
</tr>
<tr>
<td>13</td>
<td>3.55</td>
<td>0</td>
</tr>
<tr>
<td>17</td>
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<td>0.81</td>
</tr>
<tr>
<td>20</td>
<td>6.8</td>
<td>4.5</td>
</tr>
<tr>
<td>22</td>
<td>8.13</td>
<td>6.88</td>
</tr>
<tr>
<td>24</td>
<td>10.375</td>
<td>10.125</td>
</tr>
</tbody>
</table>

**Table A.2: Modified Contraction Insert Dimensions**

Figure A.1 provides a direct comparison of the original and new contractions with the mouth of the contraction oriented on the right side of the graph. The modified contraction inlet (dashed line) is markedly less abrupt than that of the original contraction (solid line).
Figure A.1: Geometries of the Original and the Modified Wind-Tunnel Contractions.
Appendix B Mechanical Considerations of Spinning Disk Construction

B.1 Safety Concerns and Stress Calculations

Spinning disks are versatile aerosol-producing instruments. They also can be very dangerous to the user and those nearby if they come loose of the motor and fly freely across the room. Disk failures can be grouped into three categories: disk imbalance, bearings failure, and disk explosion due to excessive radial stresses on the disk. Disk imbalance results from an eccentric center of mass inducing a wobble mode that stresses the shaft, leading to limit-cycle shaft failure. Careful machining of the disk should avoid this difficulty. Bearings failure occurs when the bearings holding the shaft seize up due to excessive wear or heating, subjecting the shaft to unmanageable loads. Good bearings and a clean environment help to avoid this disaster.

Disk explosion is primarily a design issue: the maximum radial stress, \( \sigma_r \), that could conceivably arise in the disk must be less than the yield strength, \( \sigma_Y \), of the material (to avoid plastic deformation of the disk). A substantial safety factor is also recommended. Young (1994) gives the following expression for \( \sigma_{r_{\text{max}}} \) concentrated at the center of a solid, rotating disk:

\[
\sigma_{r_{\text{max}}} = \frac{\rho D \pi^2 \omega^2 (3 + \nu) D^2}{8}
\]  

(B.1)

For T6061 aluminum, \( \sigma_Y = 138\text{MPa}, \nu = 0.32 \) and \( \rho_D = 2.700 \text{ kg/m}^3 \), \( D = 10.2\text{cm}, \) and \( \omega_{\text{max}} = 667\text{ rps} \) operating at the maximum rating of the air motor, \( \sigma_{\text{max}} \) was calculated to be 50MPA, compared to \( \sigma_Y = 138\text{MPa} \). The 10.2cm disks include a safety factor of almost

-253-
three, indicating that the chance of disk failure from “explosion” is remote. Sheets of plywood flanked the sides of the settling section of the wind tunnel during operation of the disks to absorb energy from the disk in case of an accident; fortunately, safe operation was maintained.

**B.2 Spinning Disk Construction**

An approximately circular piece of 0.625” thick T6061 aluminum, cut to a diameter of 2.625”, was turned on a lathe to a radius of 2.5”; the side that would serve as the spinning disk top was also faced on the lathe. The piece was then flush mounted in a 2.5” collet machined to a depth of <0.1” with the faced side towards the face of the collet; the disk thickness was ~0.1” and an additional 0.010-0.020” were allowed for clearance between the tool and the chuck. To take the piece down to the desired thickness and create the disk shaft, 0.020” cuts were taken from the outward-facing (rough) side of the piece towards the chuck. A dial indicator measured the clearance between the piece and the chuck, and the cut ended approximately 0.010” from the chuck. The cutting procedure was repeated, moving towards the center of the piece 0.020”, until the hub radius, 0.125”, was reached. The outward facing side (i.e. the bottom of the disk) was then faced to improve its finish.¹

The sharp edge of the disk was created by placing the shaft into a 0.25” collet and making cutting passes on the bottom side of the disk with the tool oriented at 30° to the disk.

---

¹ Mr. Norm Berube was instrumental in coming up with this machining procedure to construct flat and eucentric spinning disks.
Appendix C  The Pythagorean Velocity Error Correction Technique

Attempts were made to correct for the high values of $v'$ measured by the PDPA unearthed in the grid-turbulence experiments. By treating both the velocity fluctuations of the flow and the RMS error of the PDPA as independent fluctuations about the mean velocity of the flow, the correct $v'$ could be "extracted" from the PDPA measurements. The data presented in Chapter 4 reflect the application of this correction technique.

If a measurement has $n$ sources of error which are independent of each other and are random in nature, the standard deviation of the measured quantity is described by (Beckwith et al., 1982):

$$
\bar{\sigma} = \sqrt{\sum_{i=1}^{n} \sigma_{i}^2}
$$

(C.1)

Particle velocity measurements exhibit three sources of fluctuation: RMS particle velocity, $\sigma_v$, fluctuations due to long-term unsteadiness in $U$, $\sigma_m$, and PDPA error, $\sigma_p$. The combined standard deviation of $V_p$ will be:

$$
\bar{\sigma} = \sqrt{(\sigma_v^2 + \sigma_m^2 + \sigma_p^2)}
$$

(C.2)

Typically, $\sigma_m$ was much smaller than $\sigma_v$ or $\sigma_p$ over the timescale of a individual test run, in which case the measured $v'$ is approximately a composite of fluctuations in $V_p$ and error induced by the PDPA. Solving for RMS component of velocity yields:

$$
v' = \sqrt{(\bar{\sigma}^2 - \sigma_p^2)}
$$

(C.3)

A key assumption here is that $\sigma_p$ is randomly distributed and not biased towards either the high or low side of the mean, $\overline{V_p}$. The velocity measurements made at the centerline of
the open test section channel with the sprayers placed outside the tunnel to reduce freestream turbulence levels exhibited a normal, Gaussian distribution, and suggest the validity of the Pythagorean technique for filtering out accurate measurements of v'.
Appendix D  PDPA Error Assessment

D.1 Baseline RMS-Velocity Error

In the earlier attempts to quantify the background “turbulence” measured by the PDPA, the sprayers generated a level of turbulence that could be partially responsible for the apparent PDPA “turbulence”. Two sets of tests were performed using aerosol generation techniques designed to minimize the turbulence levels induced by aerosol generation.

D.1.1 Water Droplet Experiments

The Vortec Sprayvector sprayers were removed from the seeding section and generated sprays just outside of the mouth of the tunnel; the floor was covered with polyethylene plastic to minimize water damage. Because the mean tunnel flow convected the aerosols into the tunnel through the inlet straw bundle and screens, it was expected that the turbulence level created by the sprayers would be decreased. Unfortunately, $N_D$ also dropped ($N_D=50$), and reflected a dearth of larger particles (see Table D.1 and Figure D.1).

<table>
<thead>
<tr>
<th>Particle Statistic</th>
<th>Diameter ($\mu$m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_{10}$</td>
<td>3.7</td>
</tr>
<tr>
<td>$d_{20}$</td>
<td>4.7</td>
</tr>
<tr>
<td>$d_{30}$</td>
<td>5.8</td>
</tr>
<tr>
<td>$d_{32}$</td>
<td>8.8</td>
</tr>
</tbody>
</table>

Table D.1 Mean $d_p$ Statistics for Externally Mounted Sprayvector Atomizers.
Several runs measured \( v'/V \approx 0.02 \) for the smallest particles, suggesting that the RMS error of the PDPA approaches 2% on track 3.

**D.1.2 Oil Droplet Experiments**

An evaporation/condensation particle generator (see Dean, 1993) produced oil aerosols for the open channel PDPA error evaluation experiments. Mineral oil was heated in a chamber and room temperature air flowed into the top of the chamber. As the air passed over the heated oil, oil droplets condensed in the air. A higher oil temperature generally created larger droplets; however, care was taken to not burn the oil and thus avoid generating sooty, opaque particles unfit for particle sizing by the PDPA. The air stream then convected the droplets out of the chamber, through a rubber hose, and into the injection section of the wind tunnel.

The PDPA sized the oil particles\(^1\) on track 2 and revealed that virtually all the particles were less than 10\(\mu\)m in diameter (see Figure D.2) and possessed the mean values shown in Table D.2:

<table>
<thead>
<tr>
<th>Particle Statistic</th>
<th>( \mu)m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Diameter</td>
<td>2.8(\mu)m</td>
</tr>
<tr>
<td>Area Mean Diameter</td>
<td>3.5(\mu)m</td>
</tr>
<tr>
<td>Volume Mean Diameter</td>
<td>4.4(\mu)m</td>
</tr>
<tr>
<td>Sauter Mean Diameter</td>
<td>6.4(\mu)m</td>
</tr>
</tbody>
</table>

**Table D.2:** Oil Particle Mean \( d_p \) Statistics.

for a sample of over 10,000 particles. The actual mean diameters are probably significantly smaller, as the PDPA reported very large number (26,000+) of “phase under” errors

---

\(^1\) An index of refraction, \( n = 1.46 \), was used for mineral oil, compared to \( n = 1.33 \) for H\(_2\)O.
which are particles that are too small to be sized by the PDPA. In addition, over 46,000 "particle diameter over" errors were recorded, which in all probability represent additional particles that were too small to be sized.

The particle injection scheme produced lower levels of free-stream turbulence, 0.1-0.4%, than the Vortec Sprayvector (-0.5-1.0%) as measured by a hot-wire. With the PDPA on track 2, the PDPA measured the turbulence levels to be at levels from 1.35-1.70%, a value that is consistent with the turbulence levels measured for the smallest particles in the open channel water particle experiments. The background "turbulence" level inherent in the PDPA appears to be approximately 1.5-2.0%.

**D.2 PDPA Hardware Errors**

**D.2.1 Laser Beam Quality on Tracks One and Three**

After performing the experiments detailed earlier and while performing a new set of runs, the PDPA was found to have a number of hardware problems. First, the laser beam intensity varied greatly depending on what track the PDPA operated. The track 2 beam intensity was ten (10) times greater than track three and twenty (20) times greater than track 1. The beams also had a spatially non-homogeneous intensity and an elliptical shape. Upon removing the housing tube of the transmitter, the laser beam was seen to be entering the diffraction grating and beam splitter with similar intensities on all three tracks. However, the laser beams operating on both tracks two and three suffered strong degradation as they passed through the beam splitter and frequency shifting diffraction grating, indicating that the PDPA hardware was misaligned on tracks one and three. The inferior quality of the laser beams resulted in very weak signals with abnormally high noise levels; in fact, it was
the poor signal quality that led to the discovery of the transmitter misalignment. Subsequent tests were carried out using track 2 to work around the unreliable behavior of track 3 until it could be repaired. Ultimately, the transmitter was sent to Aerometrics to be realigned.

D.2.2 Ramifications for Earlier Track Three Experiments

During every test run, the quality of the PDPA Doppler bursts was observed on an oscilloscope and substandard runs were thrown out. The earlier tests produced very high quality signals that indicated that the PDPA was properly aligned: earlier tests had data rates over an order of magnitude greater than those after the misalignment was detected. Furthermore, the mean velocities measured by the PDPA agreed within experimental error with mean velocity measurements by a pitot-static probe, also suggesting that track 3 was producing credible mean velocity measurements. Also, the pre-alignment open channel experiments on track 2 (Figures 4.1 a, b and c) resemble the shape and magnitude of the post-realignment track 3 open channel tests. Finally, the grid turbulence velocity response curves before (e.g. Figures 4.5a-i) and a post-realignment open channel run (Figure D.3), although of different magnitudes because they represent different flows, possess very similar shapes; indeed, even the "notch" at \( d_p \approx 60 \mu m \) remains. Thus, it is believed that the weak, uneven beams on track 3 arose after the earlier experiments and had no tangible effect upon their results.
D.3 Published PDPA Error

D.3.1 Published Error Analyses of PDPA: Particle Sizing

Several authors have remarked that the PDPA does not accurately size smaller particles, particularly for \(d_p<5.0\mu m\). The PDPA measures particle diameter by measuring the phase lag of the particle’s signal as it registers on three spatially successive PMTs and \(d_p\) is linearly proportional to the phase lag. Sankar and Bachalo (1990) acknowledge that the presumably linear curve relating \(d_p\) and phase in fact has substantial oscillations for \(d_p<10\mu m\) which are confirmed by their computational efforts. They attribute the oscillations to the fact that as \(d_p\) approaches the wavelength of the laser, the approximate results from Mie theory that are the basis of PDPA data reductions no longer adequately describes the optical behavior of the particles. Sankar et al. (1991) size polystyrene latex particles (PSL) in air and find good agreement between their predicted and measured phase-\(d_p\) relationship. However, they report a sizing uncertainty of +/-2\mu m for \(d_p<5\mu m\) with the PDPA configured at \(\theta=30^\circ\): increasing \(\theta\) to 60\(^\circ\) decreases the uncertainty to +/-0.4\mu m. Taylor et al. (1994) published a similar study also using PSL particles to establish the PDPA (operating at \(\lambda=514nm\)) sizing errors for \(d_p<10\mu m\), as shown in Table D.3:

<table>
<thead>
<tr>
<th>PSL Sphere (d_p) ((\mu m))</th>
<th>PDPA Measured (d_p) ((\mu m))</th>
<th>PDPA Sizing Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.705 +/- 0.006</td>
<td>1.13</td>
<td>64</td>
</tr>
<tr>
<td>0.993 +/- 0.021</td>
<td>0.75</td>
<td>-24</td>
</tr>
<tr>
<td>2.062 +/- 0.025</td>
<td>2.24</td>
<td>9</td>
</tr>
<tr>
<td>5.002 +/- 0.033</td>
<td>5.72</td>
<td>14</td>
</tr>
<tr>
<td>7.040 +/- 0.057</td>
<td>7.79</td>
<td>11</td>
</tr>
</tbody>
</table>

*Table D.3*: Comparison of NIST-certified monodisperse PSL spheres to PDPA measurements (from Taylor et al., 1994)
Table D.3: Comparison of NIST-certified monodisperse PSL spheres to PDPA measurements (form Taylor et al., 1994)

These results indicate the relative inability of the PDPA to size particles less than 1μm in diameter. Note that the PDPA actually sizes the 0.705mm particles as larger than the 0.993mm particles, perhaps reflecting the oscillations in the phase-\(d_p\) curve mentioned above.

Sankar and Bachalo (1990) also discuss PDPA errors occurring at much larger \(d_p\) due to trajectory-dependent light scattering. The laser beams intersect and form a probe volume with a Gaussian light intensity distribution. When \(d_p\) is of the order of the beam diameter (\(d_b=133μm\) focused on track 3), the particle passes through regions of varying intensity and the scattered light now consists of several reflective components when the PDPA operates in the forward scatter configuration (the geometric configuration presently used). The problem is exacerbated by high number density sprays. Sankar and Bachalo estimate that with the PDPA configured at \(θ=30^°\), 25% of particle trajectories through the probe volume will yield erroneous measurements for \(d_p>20μm\). When the internally reflected light surpasses the refracted signal, the phase-\(d_p\) curve gradually decreases, with the net result that larger particles are improperly reported as smaller particles.

Particles approximately the same size as the beam, \(d_p-d_b=80μm\), create further difficulties. If a very large particle passes through an edge of the probe volume, a negative value of phase occurs between the first and third photodetectors, causing very large particles to be tagged as even larger particles. To minimize these errors, Sankar and Bachalo (1990) advocate using a beam diameter much larger than \(d_p\) whenever possible.
D.3.2 Published Error Analysis of PDPA: Number Density

Taylor et al. (1994) compared \( N_D \) measurements of the PDPA and a TSI Aerodynamic Particle Sizer (APS) for an olive oil spray. The PDPA obtains significantly lower \( N_D \) for \( d_p < 1 \mu m \), possibly due to size resolution problems at smaller diameters, while between \( d_p = 1 \) to \( 5 \mu m \), the PDPA and APS measure very similar values of \( N_D \). Typically, the PDPA presents larger \( N_D \) than the APS for \( d_p > 5 \mu m \), a discrepancy the authors attribute primarily to particle losses at the APS inlet.

D.4 Other PDPA Errors

D.4.1 Velocity Discretization Error

When the PDPA obtained velocity measurements, it does not normally store all of the exact velocity measurements; doing so would create prohibitively large data files. Instead, the PDPA software sorts the particle velocity measurements into discrete velocity bins. The bins possess the following structure: the velocity range chosen by the user to be validated for a test run consists of fifty bins which the PDPA software displays on the virtual real-time velocity histogram during a test run. Each of the fifty bins is further sub-divided into four (4) smaller bins (Kamemoto, 1992) for a total of 200 discrete velocity intervals over the measured velocity range. Typically, the velocity range for \( \bar{U} \sim 10 m/s \) will be \( \sim 5 m/s \), producing the following potential "velocity discretization" error:

\[
Error = \frac{\Delta U}{\frac{bins}{U}} = \frac{5}{200/10} = 0.0025 \tag{D.1}
\]

or 0.25%. Velocity discretization error can be considered negligible.
D.4.2 Wall Contamination

During the grid turbulence, channel flow, and secondary-flow deposition experiments, observable quantities of aerosol fluid deposit on the walls bounding the flow. Wet walls degrade the intensity and focus of the laser beam, with larger accumulations of fluid visibly refracting and even splitting the two laser beams. As a result, the quality of the PMT signal becomes progressively worse until the beams no longer intersect and the signal vanishes. The channel flow walls are particularly sensitive to water particle deposition as discussed in the “Channel Flow” section of the thesis. The surfactants used in the deposition experiments coat the surface and with time form a thin film layer that impedes efficient phase doppler anemometry. Before tests, the walls are cleaned where the laser beams and transmitter focal volume passed through the walls to obtain fully transparent and uniformly smooth walls.

D.4.3 Low-Frequency Mean Velocity Variations

All too frequently, the mean tunnel speed would abruptly change during a test run. The change in $\overline{U}$ for the run was not itself very disturbing; however, the long-term variations of $\overline{U}$, termed $U'$ here, also increased the reported fluctuating velocity of all particles, $v'$. Effectively, $U'$ masked the particle phenomenon being studied. A change in $\overline{U}$ was easily detected by observing the virtual real-time velocity distribution histogram displayed by the PDPA software during a test run, and whenever a $U'$ event was recognized, the test run was not saved and was redone.
Sudden changes in flow resistance and blower irregularity were the primary culprits. The wind tunnel operates in an open-circuit configuration, i.e. the air from the wind-tunnel room enters the tunnel and is expelled to the outdoor environment and is not recirculated. By conservation of mass, the air leaving the room must be replaced and air enters the wind tunnel room through an air filter/blower and also under the door to the room. The door to the wind-tunnel room was always kept closed and an effort was made to also keep the exterior laboratory door closed, because opening either door perceptibly altered the resistance to flow into the wind-tunnel room. Thus, when lab members would incompletely close the front door after entry, $U$ would temporarily increase, inducing an increase in $v'$ unrelated to the velocity response phenomena. Similarly, vehicles would occasionally park outside the wind-tunnel exhaust vent and the additional blockage would increase flow resistance and decrease $U$. Ultimately, physical plant posted semi-permanent "No Parking" signs by the wind-tunnel exhaust louvres to prevent further difficulties with vehicular blockage.

On rare occasions, the blower driving the vane-axial fan would exhibit irregular speed behavior (e.g. surge) despite the KB motor-controller. Careful tuning of the controller with a stroboscope to monitor the rate of motor rotation alleviated motor speed irregularities. The stroboscope visually confirmed a 0.2% variation in the blade-pass frequency of the motor.

The wind-tunnel velocity behavior from start-up was studied using a hot-wire. Subsequent to start-up, the software-controlled hot-wire sampled $\bar{U}$ once a minute, with the individual measurements lasting eight (8) seconds and consisting of 80,000 instantaneous velocity measurements averaged. Figure D.4 shows the temporal evolution of $\bar{U}$. During the first hour, $U' \sim 0.14 \text{m/s (} U'/\bar{U} \sim 1.7\%)$, while after an hour had passed, $\bar{U}$ remained essentially constant ($U'/\bar{U} \sim 0.3\%)$. A typical test run lasts 10 minutes, and the largest "low
frequency” fluctuation encountered was $U' / \overline{U}$ -0.7% during minutes 2-11; the lowest value, $U' / \overline{U}$ <0.1% occurred at the end of the experiment, providing a further indication of the longer-term stability of $\overline{U}$. Before running tests, the wind-tunnel was “warmed-up” for at least an hour to reduce $U'$ during test runs.
Figure D.1: Particle Size Distribution for Externally Mounted Vortec SprayVector Atomizer.
Figure D.2: Particle Size Distribution for Oil Droplet Generator.
Figure D.3: Track 3 Open Channel Particle Fluctuating Velocity versus $d_p$, $x=1.15$m.
Figure D.4: Temporal Evolution of Tunnel Mean Velocity from Start-up.
Appendix E  Channel Flow Experiments

E.1 The Channel Flow

The high noise levels of the PDPA were too great for the relatively low turbulence levels encountered in the approximately homogeneous turbulent flow behind a bi-plane grid. It was hoped that the higher turbulence levels at the center of a turbulent, fully-developed channel flow would be sufficient to overcome the particle RMS error induced by the PDPA.

The flow field at the centerline of a fully-developed turbulent channel flow is not precisely isotropic, and therefore also not homogeneous. Kim et al. (1987) measured all three fluctuating components of velocity at a cross-section of a turbulent channel flow (see Figure E.1). At the centerline, $u'$ is approximately 20% greater than $v'$ and $w'$, i.e. the flow is not isotropic. Moving away from the centerline, $u'$ quickly increases in magnitude, reaching a value at $y/\delta =0.5$ that is more than 50% greater than the centerline value while $w'$ and $v'$ also rise away from the centerline, although at a much lower rate than $u'$. The spatially non-uniform fluctuating components of velocity pose very real problems when attempting to assess the velocity response of aerosols because of particle history effects. A particle whose velocity is measured at the centerline, may have come to the central region of the flow from a region with a higher turbulence level. In that instance, the particle’s behavior would reflect to some degree the nature of the substantially different flow from which it came, with the past history having greater relevance for more inertial particles. Given the dearth of flows that resemble a homogeneous, isotropic turbulence, the channel flow was still considered a potential model for investigating particle-turbulence interaction, while keeping the aforementioned limitations in mind.
In a fully-developed turbulent channel flow, the velocity profile does not vary with the streamwise location. The turbulence level of the flow also reaches a steady state where the net dissipation of turbulence is precisely balanced by the extraction of energy from the mean flow by the shear stress, \( \tau_w \) at the wall. Consequentially, \( \tau_K \) may be found for a turbulent, fully-developed channel flow by obtaining the friction factor, \( f \), of the flow and solving for \( \varepsilon \). Laufer (1954) relates \( \varepsilon \) to a turbulent fully-developed channel flow friction factor:

\[
\varepsilon = \frac{4u_T^3}{D_H}
\]  

(E.1)

where \( u_T \) is the friction velocity. The integral of \( \tau_w \) around the circumference of the channel is in turn equal to the pressure gradient integrated over the cross-sectional area of the tunnel, which relates \( u_T \) to mean-flow characteristics:

\[
u_T = U_B \left( \frac{f}{8} \right)^{0.5}
\]  

(E.2)

where \( U_B \) represents the bulk velocity and \( f \), the friction factor. Blasius (1912, from Schlichting (1987)) obtained a solution for \( f \) in terms of the Reynolds Number based on the hydraulic diameter:

\[
f = 0.316 \left( Re_{D_H} \right)^{-0.25}
\]  

(E.3)

which is in turn defined by \( U_B \). It is convenient to solve for \( U_B \) from an expression for the centerline velocity, \( U_{cl} \), which is measured:

\[
U \equiv U_{cl} \left( 1 + 1.33f^{0.5} \right)
\]  

(E.4)

Thus, measuring \( U_{cl} \) and iteratively solving for \( f \) and \( \overline{U} \) (i.e. \( Re_{DH} \)) yields \( \varepsilon \) and \( \tau_K \) from eqn. 4.9 (from Section 4.5).
E.2 Channel Flow Geometry

The Aerosol Wind-Tunnel is configured for channel flow by placing two plexiglass inserts 23cm high by 122cm long by 0.3cm thick in the test section of the tunnel. The inserts, which are oriented vertically to create a channel, have plexiglass spacers to maintain a 2.5cm gap with a 9:1 aspect ratio, with \( D_h \approx 5.0 \text{cm} \). Aluminum honeycomb matrices covered the rest of the test section to equalize the flow resistance across the tunnel and minimize flow curvature at the channel inlet. Nikuradse (1932, from Hinze (1975)) found that fully developed turbulent pipe flow would occur by \( x/D_h = 25 \) to 40, whereas Latzko (1921, from Hinze (1975)) calculated \( x/D_h = 21 \). Lienhard (1987) indicates that the entry length of turbulent pipe flow is less than ten pipe diameters long; by analogy, the channel flow should be fully-developed within 10\( D_h \) of the entrance, i.e. 50cm downstream of the channel entrance. Coarse sandpaper (30-grit) covers the first 5cm of the channel walls, increasing mixing and accelerating the development of the channel flow field. Measurements of the streamwise evolution of \( U' \) and \( u' \) at the channel centerline demonstrate that neither quantity changes significantly for \( x > 11D_h \); Colmenares (1992), using an almost identical configuration, achieved a similar result. The low particle mass loading, measured to be less than 1\%, implies that the aerosols do not affect the turbulent flow field (Hestroni, 1989).

E.3 Challenges of Channel Flow Velocity Response Experiments
Channel flow velocity response experiments present several difficulties unique to the geometry. Typically, the channel flow $N_D$ ranged from 100-200 particles/cc. Figure E.2 shows a typical channel flow $d_p$ distribution in the fully-developed flow region, while Table 4.4 shows mean diameter statistics:

<table>
<thead>
<tr>
<th>Mean Diameter Statistic</th>
<th>Diameter ($\mu$m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_{10}$</td>
<td>12</td>
</tr>
<tr>
<td>$d_{20}$</td>
<td>16</td>
</tr>
<tr>
<td>$d_{30}$</td>
<td>20</td>
</tr>
<tr>
<td>$d_{32}$</td>
<td>30</td>
</tr>
</tbody>
</table>

Table E.1: Mean $d_p$ Statistics in the Fully-Developed Region of Channel Flow Experiments.

The deposition of particles on the channel side walls makes phase Doppler anemometry very difficult. Within a few minutes of beginning a test run, the walls begin to “fog up” as droplets accumulate on the wall, and the PDPA data rate gradually declines. Thicker water layers refract, and in some instances even split the laser beams, with a marked decrease in signal intensity, quality, and signal-to-noise ratio. As a result, channel flow runs are limited approximately five minutes in duration. Ten to fifteen minutes of tunnel operation with the sprayers off are allotted between runs to dry the channel walls via convective evaporation.
E.4 Dependence of Velocity Response Upon PMT Voltage

The PMT voltage, $V_{\text{PMT}}$, has a significant impact upon the validation rate and size distribution measured by the PDPA. Scattered light scales as the square of the particle diameter (i.e. with cross-sectional area), so increasing $d_p$ has a strong effect upon the signal reaching the PMT, while increasing $V_{\text{PMT}}$ increases the PMT gain and the effective amount of light measured by the PMT. A lower $V_{\text{PMT}}$ (e.g. 400V) will tend to suppress validation of smaller particles due to their weak signals, thereby skewing the apparent size distribution towards the larger $d_p$ while reducing the measured $N_D$. On the other hand, when $V_{\text{PMT}}$ is too great (e.g. 600V), the larger particles have very strong signals that saturate the PMTs and therefore are measured; these larger, rejected $d_p$ show up as "Saturation" errors on the PDPA error histogram display. Figure 3.7b provides a practical example of the effect of $V_{\text{PMT}}$ upon the measured particle distribution produced by the array generator.

Channel flow experiments carried out on track 2 indicate that choice of PMT voltage may influence $v'$ measurements. Figure E.3 summarizes ten runs, consisting of approximately 8,000 particle velocities each, at the centerline of the fully developed channel flow for three different values of $V_{\text{PMT}}$: voltages below 400V produced prohibitively low $N_D$, while $V_{\text{PMT}}>550V$ created a very noisy signal. The measured particle response for the three voltages studied and clearly show that $v'$ measurements are sensitive to $V_{\text{PMT}}$. The differences in $v'$ becomes more pronounced for larger particles and at greater $V_{\text{PMT}}$. Taken together, they suggest that the amount of light energy received by the PMT affects $v'$ measured by the PDPA. To minimize the effect of $V_{\text{PMT}}$ upon $v'$, I recommend operating the PDPA with $V_{\text{PMT}}$ at the lowest level which provides a clean signal and few PMT saturations while still possessing the capability to accurately resolve the smallest aerosols.
in a distribution. In other words, select a $V_{PMT}$ large enough such that the $d_p$ size distribution does not change appreciably when $V_{PMT}$ is increased.

The data do not clearly indicate which $V_{PMT}$ gives the "correct result for $v'$ vs. $u'$. The smaller particles of the 450V data agree rather well with experimental values of $u'$ at the centerline of a fully-developed turbulent channel flow (Kim et al., 1987). However, the flat velocity response of the larger particles disagrees with the velocity response roll-off of particles in approximately homogeneous turbulence measured experimentally by Snyder and Lumley (1971) and predicted by the theory of Hjelmfelt and Mocros (1966). Thus, it is not known if $V_{PMT}=450V$ on track 2 accurately measures particle velocity response.
Figure E.1: Transverse Distribution of Channel Flow Turbulence Quantities Normalized to $u_T$. 
Figure E.2: Particle Size Distribution for Channel Flow Experiments.
Figure E.3: Variation of Track 2 Measured Channel Flow Centerline Particle Turbulent Intensities versus \(d_p\) as a Function of \(V_{PMT}\).
Appendix F  Ultrafine Aerosol Deposition

F.1  Overview

Ultrafine aerosol deposition is of great concern in lung deposition, as 0.2μm particles contribute the largest percentage of surface area to lung deposition (NAPAP, 1990). Traditional mass transfer theory has addressed ultrafine aerosol deposition in channel and pipe flows, and boundary layers (Lienhard, 1987). Secondary flows, however, present a more challenging problem. Cohen et al. (1990) and Cohen and Asgharian (1990) found deposition rates in secondary flows to be twice as great as those predicted by theory.

The work presented in this Appendix represents an initial effort towards an understanding of ultrafine aerosol deposition in secondary flows. The experimental apparatus, aerosol generation method, and the technique for measuring aerosol deposition are described. Ultimately, the ultrafine aerosol deposition rates relative to a turbulent channel flow are presented and analyzed in the context of experimental errors.

F.2  The Ultrafine Aerosol Wind-Tunnel

A wind tunnel, simulating a turbulent channel flow, has been constructed to study ultrafine particle deposition in secondary flows (see Figure F.1). The tunnel walls are constructed entirely of Lexan to resist corrosion. A squirrel cage fan propels the air through the tunnel, generating a maximum centerline velocity of 5 m/s. To reduce the turbulence induced by the fan, the flow first passes through a honeycomb matrix (hole diameter = 0.32cm). The tunnel expands, then forms a 4:1 (area ratio) contraction and enters the planar channel, 1.27cm by 15.2cm (Dh = 2.35cm) in cross-section. To allow easy access to
the test section, the top panel of the channel may be unscrewed from the sides and removed. The Reynolds number of the channel, based on a operating velocity of 3 m/s, is approximately 5,000, surpassing the \( \text{Re}_{\text{Dh}} \geq 2,300 \) criterion for turbulent channel flow (Schlichting, 1987). Coarse sandpaper (36-grit) covers the first four inches of both the top and bottom of the channel to trip the flow and insure that the flow is turbulent. The test section vents into a fume hood.

It is desirable to make deposition measurements in a fully developed channel flow, as this flow has been thoroughly characterized hydraulically (Schlichting, 1982) and with regard to deposition (Fuchs, 1964). Colmenares (1992), Simo and Lienhard (1991) and the work contained in Chapter 2 of this thesis suggests that decaying flows may augment particle dispersion and provide further motivation for conducting experiments in a flow that does not change. Nikuradse (1932, from Hinze, 1975) determined experimentally that the velocity profile of an internal flow will be fully developed within 25 to 40 \( \text{Dh} \) from the channel entrance. Taking the value of \( \text{Dh} = 40 \) as an upper bound, fully developed flow conditions should be established at 94 cm from the test section inlet, a streamwise distance equal to three-quarters of the test section length. The sand paper trips promote flow development (Schlichting, 1982) and would tend to decrease the development length.

F.3 Aerosol Seeding

Titanium dioxide \( \text{TiO}_2 \) particles were used to study particle deposition via ultrafine aerosol deposition because they may be easily generated from titanium tetrachloride \( \text{TiCl}_4 \). In addition, \( \text{TiO}_2 \) particles range from 0.1 to 1.0 \( \mu \text{m} \) in diameter (Sarofim, 1992), largely overlapping the range of particle diameters of interest. Precise particle sizing is
obtained from transmission electron microscopy (TEM) imaging and window-driven image analysis software.

Titanium tetrachloride liquid enters the channel flow through a perforated tube (inner diameter = 0.15 cm) located five inches downstream of the blower. As the TiCl₄ comes into contact with the air convecting through the tunnel, it reacts with the moisture present in the air to form TiO₂ particles:

\[ TiCl₄ + 2H₂O → TiO₂ + 4HCl \] (F.1)

thus creating one mole of TiO₂ for each mole of TiCl₄ reacting. From this stoichiometric relation, the concentration of TiO₂ in the channel flow may be easily obtained for a given rate of TiCl₄ injection for a given air flow rate. It is assumed that the humidity present in the air is sufficient to cause all injected TiCl₄ to react.

An appropriate concentration of TiO₂ must be chosen for the test runs. A higher concentration of TiO₂ decreases the time required to achieve an appreciable level of deposition. An estimate of the effect aerosol concentration has upon run time can be found from the mass transfer analogy for internal flows, which relates the mass transfer rate to the flow conditions (Lienhard, 1987). This method predicts that appreciable deposition levels will accumulate in roughly a quarter of an hour for a TiO₂ mass loading of 1%. An upper bound on the particulate concentrations is imposed by the amount of moisture present in the air and the effect that high mass loadings have upon turbulent flows. Air of 90% humidity at 70°F consists of approximately 1.6% water by mass (CRC, 1984). Due to the stoichiometry of the TiCl₄ reaction, four moles of H₂O are required to produce one mole of TiO₂; thus, under the above conditions, the greatest possible mass loading of TiO₂ in the freestream would be 0.9%. High particulate mass loadings have been shown to damp turbulence levels (Hestroni, 1989) and would yield an inaccurate measurement of deposi-
tion rate. However, due to the relatively small particle loadings employed in our experiments, the particulate phase should have a negligible effect upon the gas phase.

**F.4 Secondary Flow Model**

A forward-backward facing step has been chosen to provide a secondary flow to study the effect of secondary flow structures upon ultrafine particle deposition. The geometry has been intensively studied by numerous authors (Bradshaw and Wong (1972), Eaton and Johnston (1981), Chandrsuda and Bradshaw (1981), Kiya and Sasaki (1985), Ruderich and Fernholz (1986), Castro and Haque (1987), O'Malley et al. (1991) and the secondary flow is well understood. The flow separates off the top of the step and a slow-moving reverse flow region evolves immediately behind the step. Further downstream, at a distance approximately nine step heights downstream of the step, the flow reattaches to the wall. Kim et al. (1984) examined deposition behind a step in a pipe flow for much larger (3.1 μm) particles with inertial characteristics and obtained deposition rates up to 100 greater than flow without a step. He attributes the remarkable increase in deposition to the wakes and flow turbulence created by step.

Guided by past experiments, square steps of $h_s = 0.32$ cm and $0.64$cm generated vigorous secondary flows in the channel. The $y$-direction aspect ratios were 0.25 and 0.5 respectively, transverse aspect ratios 0.02 and 0.04. Deposition measurements are obtained at three locations: at $x_s=3h_s$ (well fore of the theoretical reattachment point), $x_s=6h_s$ (closer to the expected reattachment length), and at $x_s=9h_s$ (at reattachment). Deposition measurements are also made in the fully developed turbulent flow region well in front of the step, providing a reference to preexisting channel flow deposition rate correlations. By placing the 0.3cm diameter TEM grids at several locations to collect depositing particles
for subsequent microscopy analysis, not only is secondary flow-enhanced deposition compared with that of a fully developed flow, but the relative location of deposition augmentation in the secondary flow structure deposition is studied. Kim et al.’s deposition rates were obtained for 2.5cm long sections ($\Delta x \sim 10h_s$), constituting an average quantity for the reverse flow region behind his obstruction, whereas the present measurements provide improved spatial resolution.

Due to the small height of the channel, the step locally increases the blockage of the tunnel and the mean flow velocity. However, the secondary flow established by the step has a far more significant effect upon deposition rate than the local increase in flow velocity.

F.5 TEM Technique


Small particles deposited on a surface can be observed by optical or electron microscopy, depending on their size. This is the primary measurement method upon which most aerosol sizing methods are ultimately based.

Transmission electron microscopy (TEM) was employed to determine the rate and spatial distribution of ultrafine aerosol deposition. The small size of the particles investigated (0.01$\mu$m to 0.5$\mu$m) and the advantages of TEM led to selection of TEM over scanning electron microscopy (SEM). TEM can resolve the smaller particles to sufficient degree of accuracy, whereas SEM cannot (Kucukcelebi et al., 1983). A Japanese Electronics Corporation (JEOL) 200kV TEM located in the Center of Material Science and Engineering was used for the preliminary studies reported herein and permits magnifications up to 330,000, resulting in 4.5 angstrom point-to-point resolution. Clearly, TEM provides adequate resolution to accurately quantify the aerosols relevant to this study. TEM also
provides a greater depth of field than SEM, resulting in superior image contrast and more accurate diameter measurements.

TEM grids affixed to the bottom channel wall collect samples of the deposited aerosol. Two concerns arose when choosing the type of TEM grid: electrostatic forces influencing the deposition rates and the profile of the grid in the flow. Upon consideration of several types of grids, 200-mesh grids with a substrate of Formvar stabilized with carbon (Rainey, 1992) were chosen. The submicron particles necessitate the Formvar substrate, so the particles deposit upon the grid and do not fall through the holes of the grid. To negate charge build-up that may interfere with TEM operation, the substrate is stabilized with carbon. The carbon coating also prevents the electrostatic deposition of particles on the grid. A thin swath of a water-based colloidal graphite paint conducts electric charge from the grids down the side of the tunnel test section. A grounded wire is held in contact with the paint by a screw, preventing charge from accumulating on the grids.

The graphite paint also adheres the tabbed grids to the wall. By flush-mounting the grids to the wall with the tabs oriented downstream of the grid, the grids do not alter the flow and influence the local deposition pattern. After a test run, the grids are removed by gently sliding a razor blade underneath the grid, freeing the grid from the thin coat of paint so that it can be manipulated with a pair of tweezers.

A software package (PC-Image by Foster Findlay Associates) analyzes the number and size of particles deposited on the grids. After the TEM photographs are developed, the negatives are placed on a light table and a CCD camera obtains a digital image of the negative. Upon saving the digital image in the computer, several routines are used to enhance the image. For example, gray-level filters analyze the image to better define the edges of the particles and provide more accurate measurements of particle diameter. The software enhances the cross-section of the smaller aerosols, which may not be very distinct in the
negative, to obtain a more accurate particle size distribution count. Post-filtering, the software assesses \( d_p \) and produces a histogram of the particle size distribution.

Photographs of particles deposited on a grid are taken near the center of the grid at a magnification of 20,000. After selecting a point almost at the center of an individual grid, the focal area traversed across much of the grid in both the \( x \) and \( y \)-directions and a photograph was taken after moving a fixed displacement to yield an essentially random survey of particles depositing on the grid. A total of ten photographs were taken for the secondary flow locations, while twenty were obtained in the channel flow to achieve a greater sample size.

**F.6 Experimental Protocol**

The tunnel walls are carefully cleaned with alcohol to remove all particulates and substances coating the wall. The TEM grids are mounted on the bottom tunnel wall and let to dry. After replacing the channel ceiling, the fan establishes the turbulent channel flow in the tunnel. Nitrogen gas forces a known volume of \( \text{TiCl}_4 \) into a line leading to the perforated injector and into the tunnel. The \( \text{TiCl}_4 \) liquid slowly drips into the entry region of the tunnel before the channel flow and reacts with the convecting moist air to form the \( \text{TiO}_2 \) aerosol. During each run enough \( \text{TiCl}_4 \) is injected to produce approximately 10 grams of \( \text{TiO}_2 \) particles. Two injections are performed each run, five minutes apart, to deliver the required volume of \( \text{TiCl}_4 \); the shorter injections decrease the risk of the \( \text{TiO}_2 \) accumulating on the injector and ultimately clogging the injector. The test runs until smoke ceases to be generated; typically, a test will last 15 minutes, i.e. ten minutes after the second injection of \( \text{TiCl}_4 \).
Initially, it was feared that a single injection site would produce an uneven aerosol concentration distribution throughout the cross-section of the tunnel. However, visual observation of the flow suggests that the honeycomb, working in tandem with the expansion and contraction sections, achieves an even spatial distribution of the TiO$_2$ aerosol before the particles reach the test section.

**F.7 Results**

Deposition measurements of TiO$_2$ particles in a fully-developed channel flow with and without a 0.32cm step were acquired using the TEM technique detailed above. In the baseline run (i.e. sans secondary flow generated by a step), 14.2 grams of TiO$_2$ were generated with the tunnel operating at $U = 2.8$ m/s, while 8.2 grams were produced during the run with a step and $U = 2.5$ m/s. The step presented additional blockage to the flow, accounting for the slightly lower velocity during the run with a step. The discrepancy in TiO$_2$ generated can be attributed to the injection system, which requires additional refinement. A normalized deposition rate was attained by normalizing the deposited aerosol counts by the injected mass ratio of the two runs.

The TEM grids placed in the two flows were analyzed to compare deposition rates. Scanned across a grid revealed that each sector of the grid appeared to have approximately the same number of deposited particles, implying that a count of one sector of a grid yields a representative deposition measurement for the entire grid. Thus, a single sector of each grid was interrogated by carefully traversing across the center of the sector to average out local particle count variations.

Figure F.2 presents a histogram of aerosols deposited in the baseline case, within the recirculation zone, and at reattachment normalized for inter-test TiO$_2$ concentration varia-
ation. The data, although somewhat small in number, exhibit several interesting trends. The preliminary data indicate that a secondary flow greatly enhances ultrafine particle deposition. Within the secondary flow, at \( x_s = 6h_s \), the deposition rate is almost seven times greater than the baseline while the reattachment point rate over three times higher. A glance at the size distribution of deposited particles (Figure F.3) indicates that the TiCl\(_4\) primarily generates TiO\(_2\) particles between 0.02\(\mu\)m and 0.5\(\mu\)m in diameter, precisely in the range of interest.

One concern was that the secondary flow would preferably augment the deposition of larger, somewhat inertial aerosols due to impaction, obfuscating our study of the diffusive deposition mechanism. The deposition histogram does not show a bias of the step particle counts towards larger particles; in fact, the opposite trend occurs, probably due to the small sample size.

**F.8 Unknowns and Sources of Error**

There are numerous flaws with the ultrafine deposition experiments. The number density, \( N_D \), of the TiO\(_2\) particles in the flow remained unknown throughout the test runs. The volume of TiCl\(_4\) entering the test section was estimated by obtaining a estimated flow velocity of the TiCl\(_4\) and assuming it remained constant for the entire injection time. Clearly, a very significant portion of the TiO\(_2\) did not pass through the tunnel and instead formed upon the injector and the surface of the wind tunnel below the injector. In addition, many of the TiO\(_2\) particles deposited on the honeycomb flow straightener located between the injection site and the channel flow entrance. The bulk of the TiCl\(_4\) was injected towards the outset of the test runs, creating higher TiO\(_2\) concentrations initially that decayed with time in an unknown fashion. The time-dependence of concentration was assumed to have
no effect upon overall deposition levels, i.e. only the net mass of TiO2 was considered important; the validity of this assumption was unknown.

The size distribution of the TiO2 particles in the flow also could not be measured, making calculation of a deposition rate based on $St_k$ (for more inertial aerosols) or $D$ (for smaller, Brownian-motion dominated aerosols) impossible. In short, the deposited aerosol size distribution cannot be assumed to represent the size distribution present in the flow.

The fully-developed turbulent channel flow (baseline) and secondary flow deposition experiments were not run at same time. Although efforts were made to insure that flow and particularly injection conditions were similar, the inconsistency of the injection system casts doubts upon the similarity of the two tests.

Feng (1993), in a subsequent effort, improved the TiCl4 injection system by carefully controlling the volume of TiCl4 entering the tunnel with a buret. He also obtained fully-developed channel flow and secondary flow deposition rates simultaneously, further alleviating concerns of inconsistency between runs. Unfortunately, the study of Feng (1993) suffered from even smaller sample sizes than the test reported herein. The TEM images appear to be contaminated with low-density crystalline particles in several instances, casting doubts upon the deposition counts obtained by the imaging software.

**F.9 Conclusions**

The deposition experiments appear to indicate that secondary flow structures augment the deposition rates of ultrafine aerosols. This conclusion is tenuous at best. As detailed under the section "unknowns and sources of error", very poor control was exercised over several important aerosol parameters. Inter-run variations are believed to be large and could not be quantified, raising doubts about the validity of comparing baseline and secondary flow
deposition counts measured during different test runs. Finally, Feng (1993), using an improved aerosol generation system and simultaneously obtaining baseline and secondary deposition counts, found higher deposition rates in the turbulent channel flow than in the secondary flow. Thus, the deposition of ultrafine aerosols in secondary flow experiments must be considered inconclusive in even a qualitative sense.
Figure F.1: The Ultrafine Aerosol Wind Tunnel: (from Feng, 1993).
Figure F.2: Variation of Total Particle Deposition Count with x/h.
Figure F.3: Variation of Deposited Aerosol Size Distribution with $x/h$. 

![Graph showing variation of deposited aerosol size distribution with x/h.](image-url)