A STUDY OF THE FLOW THROUGH ULTRAVIOLET DISINFECTION SYSTEMS

by

Pierluigi Cozzi

A thesis submitted in conformity with the requirements for the degree of Master of Applied Science
Graduate Department of Mechanical Engineering
University of Toronto

© Copyright by Pierluigi Cozzi, 1996.
The author has granted a non-exclusive licence allowing the National Library of Canada to reproduce, loan, distribute or sell copies of this thesis in microform, paper or electronic formats.

L’auteur a accordé une licence non exclusive permettant à la Bibliothèque nationale du Canada de reproduire, prêter, distribuer ou vendre des copies de cette thèse sous la forme de microfiche/film, de reproduction sur papier ou sur format électronique.

The author retains ownership of the copyright in this thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without the author’s permission.

L’auteur conserve la propriété du droit d’auteur qui protège cette thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation.

0-612-45452-5
A Study of the Flow Through Ultraviolet Disinfection Systems

Pierluigi Cozzi

Master of Applied Science
Graduate Department of Mechanical Engineering
University of Toronto
1996

Abstract

In this work, the hydraulic characteristics of an ultraviolet wastewater disinfection unit were studied. A commercially available system manufactured by Elsag Bailey (Canada) Inc. was placed in an open channel flume. Measurements were made over a range of channel velocities from 20 to 60 cm/s. Dye was injected into the flow and videotaped in order to provide both a qualitative and quantitative analysis of the mixing occurring within the disinfection unit. Velocity measurements were conducted along the length of the unit using an Acoustic Doppler Velocimeter and from this data the overall turbulence intensity within the unit was estimated. The design of the unit was altered by reshaping the upstream ends of the unit and by installing washers along the length of the quartz sleeves. It was found that the addition of washers significantly increased the mixing throughout the unit and is expected to improve considerably the disinfection efficiency of the wastewater system. Microbiological tests are being conducted currently by Elsag Bailey to quantify this increase in efficiency.
Acknowledgments

I would like to thank my thesis advisor, Professor Mark Loewen for his guidance and many insightful suggestions throughout this entire project. I would also like to thank my thesis committee, Professor Baines and Professor Sullivan for reading and evaluating my work. Thanks also to Dr. Elliott Whitby for his help in answering questions and for providing research resources and thanks to Elsag Bailey (Canada) Inc. for funding this research.

I would like to express my love to Mom, Dad and Sarah for their support and understanding throughout.

A sincere thanks to all the friends that I have made and with whom I worked with in the lab. Their zaniness provided comic relief and their willingness to share their insights was most helpful and appreciated. Thanks Matthieu, Lexy, Cesar, Cathie, Matt and Mark (a breath of fresh air) and everyone else.

I would like to express my gratitude to Katharine Hancock whose continuous help and friendship was greatly appreciated.

Thanks also goes out to all my friends, especially Rob & Jen, Jason & Dee, Kevin Oickle and Jason Ehl, for their constant encouragement and support.

I would also like to thank Len Roosman for his help setting up the channel and for answering all my questions. Thanks also to Paul and Jeff in the machine shop for their additional technical help.

And last, but definitely not least, special thanks goes to Claire Ser dul a for keeping me sane on many occasions and by helping me immeasurably. Thank you.
# Table of Contents

Abstract .............................................................................................................................. ii

Acknowledgements ............................................................................................................. iii

List of Tables ....................................................................................................................... v

List of Figures ................................................................................................................... vi

List of Appendices ............................................................................................................. ix

Nomenclature ...................................................................................................................... x

1. Introduction ................................................................................................................... 1
   1.1. Motivation ............................................................................................................... 3
   1.2. Ultraviolet Reactors ............................................................................................. 4
   1.3. Hydraulic Design of Ultraviolet Reactors .......................................................... 6
   1.4. Objectives ............................................................................................................. 15

2. Design Alternatives ...................................................................................................... 17

3. Experimental Methodology ......................................................................................... 20
   3.1. Preliminary Flow Visualization Experiments ......................................................... 21
   3.2. Acoustic Doppler Velocimeter (ADV) Experiments ............................................... 24
   3.3. Quantitative Flow Visualization Experiments ....................................................... 29

4. Results .......................................................................................................................... 32
   4.1. Preliminary Flow Visualization ............................................................................. 32
   4.2. Maximum Operating Velocity .............................................................................. 33
   4.3. Water Surface Profiles ......................................................................................... 35
   4.4. Velocity Distributions .......................................................................................... 39

5. Analysis ........................................................................................................................ 43
   5.1. Turbulence Intensity and Standard Deviation plots ............................................... 43
   5.2. Quantitative Flow Visualization Tests .................................................................... 51
   5.3. Residence Times .................................................................................................... 59

6. Conclusions ................................................................................................................... 61
   6.1. Summary of Results ............................................................................................. 62

7. Recommendations ........................................................................................................ 65

8. List of References ......................................................................................................... 67

9. Appendices ...................................................................................................................... 69
List of Tables

Table 2-1: Different rack configurations tested: for racks G, J, K, L, M, N, O, and P, the modifications, e.g. the washers, were implemented on the original rack (rack E). .... 18

Table 4-1: Values for the maximum operating velocities and rack blockages. ................. 35

Table 5-1: Area under and maximum peaks of the turbulence intensity curves for racks with washers and racks E and Q................................................................. 48

Table 5-2: Plume spreading calculations for racks at a channel velocity of 30 cm/s.
Ψ - plume spread calculated from the slope of the linear regression lines of best fit.
Φ - plume spread calculated from the slopes of the first and last sampling points.
(Complete results of plume spreading are found in appendix A, Table A-4) ............ 55

Table 5-3: Residence times for racks with washers and for racks E and Q with a lamp length of 1.47 m.......................................................................................... 60

Table 6-1: Non-dimensionalized average turbulence intensity data for racks with washers and racks E and Q at a channel velocity of 30 cm/s and at positions 1 and 2. All racks have been non-dimensionalized with respect to rack E. ....................... 62

Table 6-2: Non-dimensionalized plume spreading rates at a channel velocity of 30 cm/s.
All values have been non-dimensionalized with respect to rack Q. ΨQ is the spreading rate of rack Q. ................................................................. 63

Table 6-3: Non-dimensionalized residence times for racks with washers and racks E and Q at a channel velocity of 30 cm/s and at positions 1 and 2. All racks have been non-dimensionalized with respect to rack E........................................... 64

Table 7-1: Velocity histogram data collected from wastewater treatment plants. Velocity bins are 5.63 cm/s wide............................................................. 65
List of Figures

Figure 1-1: (Left) Ultraviolet radiation being absorbed by the DNA molecule. (Right) Successful joining of the adjacent thymines forming a thymine dimer. Molecules: A = adenine, T = thymine, G = guanine and C = cytosine. ................................. 2

Figure 1-2: Example of a parallel flow enclosed reactor unit [EPA, 1986]. ......................... 5

Figure 1-3: Schematic of the Elsag Bailey UV unit............................................................. 6

Figure 1-4: Light intensity in between four UV lamps within a disinfection unit as calculated by the point source summation method [EPA, 1986].................................................. 8

Figure 1-5: Simulated RTD plot with time parameters $t_c$ - the time at which the tracer first appears, $t_{10}$ - time at which 10% of the tracer passes, $t_p$ - time at which the peak concentration occurs, $T$ - theoretical residence time and $t_{90}$ - time at which 90% of the tracer passes. .................................................................................................................. 10

Figure 2-1: Rack configurations of upstream rack supports and washers. ....................... 19

Figure 3-1: Video setup used in flow visualization experiments ............................... 22

Figure 3-2: The transverse locations (I-V) where dye was injected for the preliminary flow visualization experiments................................................................. 23

Figure 3-3: The axial locations of the dye injection points for the preliminary flow visualization tests. Position 1 - upstream entrance. Position 2 - 1/3 the rack length downstream, position 3 - 2/3 of the rack length downstream. ........................................ 24

Figure 3-4: Schematics of the ADV probe. (a) Coordinate system of the ADV 3-D side looking probe. (b) Dimensions of the ADV probe. (c) Position of the sampling volume of the ADV down looking probe................................................................. 25

Figure 3-5: ADV positioned in the channel to test for flow interference at different probe angles ...................................................................................................................... 26

Figure 3-6: Axial locations of ADV sampling points for racks with modified upstream supports .............................................................................................................. 27

Figure 3-7: Axial locations of ADV sampling points for racks with washers.................. 28

Figure 3-8: Transverse position of ADV sampling points ............................................. 29
Figure 3-9: Dye injection points for the quantitative flow visualization experiments (a) Side view of channel and dye injection points. (b) Cross-sectional view of channel and injection points. (c) Close up view of injection point 2. .......................... 31

Figure 4-1: Images of the preliminary flow visualization experiments for rack E at dye injection point I and a water velocity of 30 cm/s. (a) Entrance to the rack, (b) 50 cm downstream of the rack entrance. .................................................. 32

Figure 4-2: Water surface profiles at 30 cm/s, a water surface elevation of -1 cm corresponds to the top of the uppermost quartz sleeves. The rack entrance is at y = 0 cm and the exit is at y = 170 cm. (a) Rack E. (b) Rack J, washers are positioned at 47 cm and 113 cm downstream of rack entrance. .................................................. 37

Figure 4-3: Water surface profiles at 50 cm/s, a water surface elevation of -1 cm corresponds to the top of the uppermost quartz sleeves. The rack entrance is at y = 0 cm and the exit is at y = 170 cm. (a) Rack E. (b) Rack J, washers are positioned at 47 cm and 113 cm downstream of rack entrance. .................................................. 38

Figure 4-4: Mean velocity components versus y at transverse position 2 for rack E at a channel velocity of 30 cm/s. Rack entrance at y=0 cm, exit at y=160 cm. (a) x-component. (b) y-component. (c) z-component. .................................................. 40

Figure 4-5: Velocity versus y measured at transverse position 2 for rack P at a channel velocity of 30 cm/s. Rack entrance at y=0 cm, exit at y=160 cm. (a) x-component. (b) y-component. (c) z-component. .................................................. 41

Figure 4-6: Velocity versus y measured at transverse position 2 for rack R at a channel velocity of 30 cm/s. Rack entrance at y=0 cm, exit at y=160 cm. (a) x-component. (b) y-component. (c) z-component. .................................................. 42

Figure 5-1: A typical turbulent velocity time series. .................................................. 43

Figure 5-2: Turbulence intensity versus axial distance y for a channel velocity of 30 cm/s at transverse position 2. y=0 cm is the entrance to the rack. (a) Rack E. (b) Rack Q. .................................................. 45

Figure 5-3: Turbulence intensity as a function of the axial distance y for Rack P at a channel velocity of 30 cm/s, at transverse position 2. .................................................. 46

Figure 5-4: RMS velocities at position 2 for rack E. Rack entrance at y=0 cm. (a) Channel velocity 30 cm/s. (b) Channel velocity 50 cm/s. .................................................. 49

Figure 5-5: RMS velocities at position 2 for rack P. Rack entrance at y=0 cm. (a) Channel velocity of 30 cm/s. (b) Channel velocity of 49 cm/s. .................................................. 50
Figure 5-6: Dye plume in Rack K at a channel velocity of 30 cm/s. Axis labels are pixel numbers. (a) Single image. (b) Composite image. (20 images combined) .......................... 52

Figure 5-7: Composite images at a channel velocity of 30 cm/s, 108 cm downstream of rack entrance at dye injection point 1. Axis labels are pixel numbers. (a) Rack Q. (b) Rack K. ........................................................................................................... 53

Figure 5-8: Schematic of plume spreading measurements. ......................................................................................... 54

Figure 5-9: Composite images at a channel velocity of 30 cm/s at dye injection point 2. Axis labels are pixel numbers. (a) Rack Q. (b) Rack K. ................................................................. 57

Figure 5-10: Composite images at a channel velocity of 30 cm/s at dye injection point 3. Axis labels are pixel numbers. (a) Rack Q. (b) Rack K. ......................................................... 58
List of Appendices

Appendix A - Additional Data ................................................................. A-1
Appendix B - Error Analysis................................................................. B-1
Appendix C - Water Surface Profiles .................................................. C-1
Appendix D - Velocity Profiles ............................................................. D-1
Appendix E - Turbulence Intensity Plots .............................................. E-1
Appendix F - Standard Deviation Plots .................................................. F-1
Nomenclature

Variables

\( A_b \)  \hspace{1em} \text{cross-sectional area of obstruction}
\( A_i \)  \hspace{1em} \text{average turbulence intensity}
\( A_T \)  \hspace{1em} \text{total cross-sectional area}
\( B_l \)  \hspace{1em} \text{blockage}
\( B_m \)  \hspace{1em} \text{bulk modulus}
\( c \)  \hspace{1em} \text{speed of light}
\( C_{\text{conc}} \)  \hspace{1em} \text{concentration}
\( c_w \)  \hspace{1em} \text{speed of sound in water}
\( d \)  \hspace{1em} \text{dispersion coefficient}
\( d_i \)  \hspace{1em} \text{downstream distance of the } i^{th} \text{ velocity measuring point}
\( D_{\text{ad}} \)  \hspace{1em} \text{administered dosage}
\( E_{\text{UV}} \)  \hspace{1em} \text{energy of the ultraviolet light}
\( f_i \)  \hspace{1em} \text{frequency of the original signal}
\( \Delta f \)  \hspace{1em} \text{change in frequency}
\( h \)  \hspace{1em} \text{downstream water height}
\( h_p \)  \hspace{1em} \text{Planck’s constant}
\( \Delta h \)  \hspace{1em} \text{head difference}
\( i \)  \hspace{1em} \text{index}
\( I \)  \hspace{1em} \text{light intensity}
\( I_T \)  \hspace{1em} \text{turbulence intensity}
\( k_d \)  \hspace{1em} \text{inactivation constant}
\( l \)  \hspace{1em} \text{length of rack}
\( q \)  \hspace{1em} \text{flow rate}
\( r_d \)  \hspace{1em} \text{rate of inactivation}
\( \text{RTD} \)  \hspace{1em} \text{residence time distribution}
\( t \)  \hspace{1em} \text{time}
\( t_i \)  \hspace{1em} \text{\( i^{th} \) time}
T theoretical residence time
t_r time at which tracer first appears
t_{10} time at which 10% of the tracer has past
t_p time at which the peak concentration occurs
t_{90} time at which 90% of the tracer has past
\Delta t time interval between t_i and t_{i+1}
\Delta t_{i\rightarrow i+1} time increment from
u axial velocity
V channel velocity
V(t) velocity as a function of time
V_i velocity of i^{th} measuring point
V_v void volume
V mean velocity
V' fluctuating velocity component
V'^2 mean square of fluctuating velocity
w width of channel
x coordinate direction of Cartesian space as defined in the thesis
x_o position of first velocity sampling point
x_r position of last velocity sampling point
y coordinate direction of Cartesian space as defined in the thesis
z coordinate direction of Cartesian space as defined in the thesis

Symbols

\phi angle
\lambda wavelength
\theta mean residence time
\rho density
\( \sigma \) variance
\( \sigma_h \) variance in water height
\( \sigma_Q \) variance in flow rate
\( \sigma_v \) variance in channel velocity
\( \tau \) averaging time
\( \Phi \) total slope of the spread of the plume calculated by line through end points
\( \Psi \) total slope of the spread of the plume calculated by line of best fit
\( \Psi_o \) total slope of the spread of the plume calculated by line of best fit for rack Q
1. Introduction

In the past, the disinfection of wastewater has been accomplished through the use of chlorination. This process however is plagued with some potentially serious consequences. Through the reaction of chlorine with certain organic materials present in the wastewater, by-products are formed and these have been shown to be carcinogenic [Voutchkov, 1995]. Wastewater discharges from chlorine disinfection plants into rivers have also been found to be extremely toxic to the aquatic species living in these water bodies [EPA, 1986; Whitby et al., 1984; Cairns, 1995]. In addition, there is also the associated danger of chlorine gas leaks due to equipment failure or operator error. With stricter government control being implemented as per the U.S. 1994 Clean Water Act, it is imperative that more environmentally acceptable processes be investigated and implemented [Voutchkov, 1995].

Due to these growing concerns associated with chlorination, there has been increased interest in recent years in the use of ultraviolet (UV) light for disinfection of wastewater. Ultraviolet light can be found on the electromagnetic spectrum just to the left of visible light with a wavelength ranging from 40 nanometers (nm) to 400 nm. The energy $E$, associated with a given wavelength of light $\lambda$, is governed by:

$$E_{uv} = \frac{h \cdot c}{\lambda}$$

(1)

where $h = 4.136 \times 10^{-15}$ eV·s (Planck’s constant) and $c = 2.998 \times 10^8$ m/s (speed of light) [Brehm and Mullen, 1989]. As a result, the electromagnetic waves that are at the right side of the spectrum are less energetic than those to the left. The UV radiation which is
used primarily for the purposes of wastewater disinfection has wavelengths of approximately 260 nm to 280 nm [Nieuwstad et al., 1991 and EPA, 1986].

The genetic information of a cell is contained within its deoxyribonucleic acid (DNA) and ribonucleic acid (RNA). A cell's DNA consists of groups of nucleotides linked together in a double helix shaped chain. A segment of the DNA molecule is shown below in Figure 1-1. In a healthy cell, the molecules of adenine are paired opposite to thymine, those of guanine opposite to cytosine and their order determines genetic traits. UV light with a wavelength of approximately 250 nm is readily absorbed by the pyrimidines (the thymines or the cytosines) and the energy imparted to these may cause damage to their bonds. If a photon (an energy packet of light) with sufficient energy to cause damage is absorbed, a double covalent bond may then be created between similar adjacent pyrimidines known as dimers. The creation of thymine dimers occurs more readily than the formation of the cytosine dimer but the formation of either of these double bonds can inhibit the replication of the cell. [Raven & Johnson, 1989 and EPA, 1986]. In summary, large doses of UV light will exterminate disease causing pathogens.

![Diagram of Ultraviolet Light and DNA](Image)

**Figure 1-1:** (Left) Ultraviolet radiation being absorbed by the DNA molecule. (Right) Successful joining of the adjacent thymines forming a thymine dimer. Molecules: A = adenine, T = thymine, G = guanine and C = cytosine.
In order to successfully produce these mutations, the organisms must be exposed to a sufficient dosage of ultraviolet light. The required minimum dosage will vary with each organism [Rice and Hoff, 1981]. The dose is defined as,

\[ D_{\text{ad}} = I \times t \]  

where \( D_{\text{ad}} \) is the dosage administered (Watts·s per cm\(^2\)), \( I \) is the intensity or power per unit area radiated by the UV lamp (Watts per cm\(^2\)) and \( t \) is the exposure time of a given pathogen in seconds. Unlike chlorine, UV light does not produce any trace residuals and therefore determining exact dosages is rather difficult. Qualls et al.[1989] and Nieuwstad et al.[1991] have successfully utilized average UV intensities and average residence times along the entire volume of a disinfection unit to evaluate UV dosages.

1.1. Motivation

Bioassay studies were conducted by HydroQual Inc. [1990, 1993, 1994a, 1994b] on several commercial UV disinfection units manufactured by Elsag Bailey (Canada) Inc.. The studies examined the hydraulic characteristics of the reactors and derived relationships between applied UV dosage and flow rate. Identical testing was conducted for a similar disinfection unit that is manufactured by one of Elsag Bailey's leading competitors and it was found that at low flow rates, the competitor's system administered a larger UV dose. However, at higher flow rates, the Elsag Bailey unit was more effective, i.e. it delivered a higher UV dose. Consequently, Elsag Bailey decided that it should attempt to improve the performance of its system particularly at the lower flow rates. It was hypothesized
that the performance could be improved by increasing transverse mixing within the UV unit [Dr. G. E. Whitby, per. comm.].

1.2. Ultraviolet Reactors

While the individual designs of ultraviolet disinfection units may differ considerably, there are essentially two basic UV reactor configurations [EPA, 1986]. One design arrangement consists of an array of UV lamps that surround a series of clear Teflon tubes. Wastewater flows into the reactor from a common inlet and is diverted into these UV transparent conduits. The UV lamps are positioned parallel to the wastewater flow and disinfection occurs as the light from the lamps strikes the transparent tubes. In the other type of reactor the UV lamps are encased inside water-tight, UV transparent quartz sleeves which are immersed in the stream of wastewater. Some reactors are designed so that the entire lamp array is held within an enclosed conduit. Flow of untreated wastewater is passed through an inlet pipe perpendicular to the lamps. The flow is then redirected down the length of the reactor and the disinfected effluent exits the unit perpendicular to the lamps. Some of these reactor type disinfection system may also place the lamps perpendicular to the flow. Figure 1-2 shows an example of the parallel flow enclosed reactor unit.

The most widely used system, utilizing the quartz sleeves, is designed to be placed in open channels; the Elsam Bailey system is of this type. The UV lamps are positioned in an equally spaced array (both horizontally and vertically) and are placed parallel to the direction of flow. This UV system is highly modular as the lamps are held together in
individual vertical units with the number of lamps in each unit set to match the water depth. These units are easily joined with others to form the matrix of lamps and therefore a number of these can be linked together to span any width of channel. The sections are easily removed for cleaning purposes. A diagram of the Elsag Bailey unit is shown below in Figure 1-3.

Figure 1-3: Schematic of the Elsag Bailey UV unit.

1.3. Hydraulic Design of Ultraviolet Reactors

Regardless of their exact configurations, each disinfection unit should adhere to certain hydraulic design criteria [EPA, 1986]. Ideally, the flow through the reactor will exhibit plug flow characteristics. In plug flow there is very little longitudinal mixing
(mixing along the length of the UV lamps for lamps that are positioned parallel to the flow of wastewater) and therefore all fluid elements (or particles) will remain within the reactor for approximately the same length of time. Particles which quickly traverse the unit or ‘short circuit’ the reactor will not receive a large enough UV dose for inactivation and hence they may not be adequately treated.

In addition, radial mixing should be kept to a maximum throughout the reactor. The importance of adequate radial mixing is illustrated in Figure 1-4 which shows the UV intensity profile found between four parallel lamps. The profile is non-uniform and therefore in order to ensure that all pathogens receive a similar UV dose it is necessary to transport them throughout the cross-section. However, as the radial mixing is increased, there will be a corresponding increase in longitudinal mixing [Severin et al., 1984].

Another design consideration is the need to limit the formation of ‘dead zones’; areas within the reactor which exhibit little or no flow. These regions decrease the total volume in which disinfection may occur and as a result can severely restrict the disinfection efficiency of the unit. Headlosses are another important consideration in the design of these systems. Depending on the specific wastewater treatment plant, it may be necessary to place several UV units in series. As a result, the headlosses which occur across one reactor will be transferred to the upstream units. An adequate amount of wastewater flowing over the quartz sleeves helps facilitate heat transfer from the lamps and inhibits the premature buildup of residue over the sleeves. An excess of water however, may inhibit pathogen inactivation as particles that are trapped in these upper layers away from the lamps may not receive an adequate UV dose. Therefore, Elsag
Bailey recommends that their units be operated with a minimum of approximately 5 mm and a maximum of approximately 25 mm of water above the uppermost row of sleeves.

Figure 1-4: Light intensity in between four UV lamps within a disinfection unit as calculated by the point source summation method [EPA, 1986].
The above discussion qualitatively describes some of the design considerations for an ideal UV disinfection unit however, work has been done to quantify the hydraulic performance of flow through reactors [EPA, 1986 and Levenspiel, 1972]. As a single particle passes through a UV reactor it will remain within the unit for a given length of time denoted as its residence time. By following the paths of many particles and subsequently computing their individual residence times it will be possible, if enough particles are sampled, to determine a residence time distribution (RTD) representative of that specific disinfection unit. The RTD curve can be measured in different ways, the easiest being; the pulse input method or the step input technique. The pulse input method is accomplished by quickly injecting a tracer pulse some distance upstream of the UV unit. Downstream water samples are then taken to monitor the change in concentration of the tracer and a plot of concentration versus time can be constructed. The step input technique is accomplished by injecting a continuous stream of tracer upstream of the unit and allowing a steady-state concentration to develop. The injection of the tracer is then stopped and downstream water samples are taken to observe the decrease in tracer concentration from its maximum steady-state value. The curve constructed from the decreasing concentration divided by the original concentration, when plotted versus time is called an F curve. In order to construct an RTD plot from the step input method it is necessary to compute the time derivative of the F curve.

The shape and area contained underneath the RTD curve can be used to determine several of the hydraulic characteristics associated with the disinfection unit. Shown in Figure 1-5 is an example of a typical RTD plot.
Figure 1-5: Simulated RTD plot with time parameters $t_r$ - the time at which the tracer first appears, $t_{10}$ - time at which 10% of the tracer passes, $t_p$ - time at which the peak concentration occurs, $T$ - theoretical residence time and $t_{90}$ - time at which 90% of the tracer passes.

From this RTD curve is it now possible to define some hydraulic characteristics which represent this UV unit. For instance, the theoretical residence time, $T$, of the unit is defined by:

$$T = \frac{V_v}{q}$$  \hspace{1cm} (3)

where $V_v$ is the void volume of the reactor and $q$ is the flow rate in the channel. The ratio of the time at which the tracer first appears, $t_r$, to $T$ is a measure of the most extreme short-circuiting in the reactor. In a perfect plug flow reactor this ratio is one and it will approach zero as mixing is increased. The ratio of the time at which peak concentration occurs, $t_p$, to $T$ will also equal one in a plug flow reactor and approach zero with increased mixing. This ratio is a measure of the average degree of short-circuiting and will also reveal the presence of dead zones within the reactor if its value approaches zero. Defining the mean residence time, $\theta$, as:
\[
\theta = \frac{\int_0^\infty t C \, dt}{\int_0^\infty C \, dt} \equiv \frac{\sum_i t_i C \Delta t_i}{\sum_i C \Delta t_i}
\]  

where \( C_{\text{ave}} \) is the concentration of the tracer and \( t \) is time. The ratio of \( \theta \) to the theoretical residence time \( T \), will give an indication of whether or not the entire volume of the reactor is being fully utilized. This ratio should approach one for an efficient reactor design and values significantly less than one signify that the effective volume of the unit has been greatly decreased. The Morrill Dispersion Index \((t_{90}/t_{10})\) is defined as the ratio of the time for 90% of the tracer to pass through the unit, to the time for 10% of the tracer to pass. This parameter will equal one in a perfect plug flow reactor and 21.9 in a completely mixed unit [EPA, 1996].

Additional information can be derived from the spread of the RTD curve which will estimate the longitudinal dispersion coefficient.

\[
d = \frac{\varepsilon}{u \, l}
\]

By defining the dispersion number \( d \), as the ratio of the longitudinal dispersion coefficient, \( \varepsilon \), to the axial velocity \( u \), multiplied by the length of the UV unit, \( l \), it is possible to write a differential equation representing the longitudinal dispersion within the reactor. As the value of \( d \) tends towards zero there is negligible dispersion occurring and the reactor will exhibit plug flow characteristics. Conversely, as \( d \) increases in value, the dispersion grows producing mixed flow conditions. For reactors which display little dispersion \((d<0.01)\) the RTD curve approaches a normal distribution and therefore it is possible to directly relate the shape of the curve to the dispersion number. By identifying the variance of the RTD
curve $\sigma$, and calculating the mean residence time $\theta$, it is possible to estimate the dispersion number from the following relation [Levenspiel, 1962].

$$\frac{\sigma^2}{\theta^2} = 2 \left( \frac{\varepsilon}{ul} \right) = 2d \quad (6)$$

Listed in appendix A, Table A-6 are the results from a HydroQual, Inc. (1994b) residence time analysis on the Elsag Bailey disinfection unit. Examination of the above ratios derived from the RTD curve indicate that this reactor exhibits the characteristics of a plug flow reactor and its dispersion number was calculated as 0.019 suggesting that it operates with low longitudinal dispersion.

Some of the earliest experiments that examined the variables which control UV disinfection efficiency were performed by Cortelyou et al. [1954]. They used a small, one-lamp ultraviolet water purifier designed for home use. Disinfection efficiency was described in terms of both exposure time and mixing characteristics. Prior to each test, various species of bacteria and other organisms were prepared and their respective populations were determined. During the initial experiments, known quantities of bacteria were introduced to the UV unit and from the unit’s discharge, samples were obtained and counts of remaining bacteria were taken. The ratio of the initial population of bacteria to the population of treated bacteria is defined as the kill ratio. In subsequent experiments, the flow patterns present within the UV unit were altered by means of baffles or by modifying the entrance delivery tube. By implementing these changes it was possible to force the bacteria to remain in areas of increased UV intensity and as a consequence receive a larger dose of UV light. Each test was conducted at four separate flow rates.
Cortelyou et al. [1954] set up their experiments so as to achieve an inverse relation between rate of flow and duration of exposure to the UV light. As a result, as the flow rate increased the disinfection efficiency of the unit decreased; these effects were observed during the first tests. When the flow patterns were altered by the addition of baffles or by modifications to the disinfection unit's inlet however, there was a marked increase in the resulting kill ratios at all flow rates. It was concluded that since there was a decrease in the exposure time due to the faster flow rates, the increased mixing must have offset this effect and created an overall increase in the kill ratio.

The modeling work conducted by Hass and Sakellaropoulos [1979] analyzed the theoretical performance of different reactor designs. Their models utilized first-order inactivation kinetics \( r_d = -k_d I C_{\text{conc}} \) where \( r_d = \) rate of inactivation, \( k_d = \) inactivation rate constant, \( I = \) incident radiation and \( C_{\text{conc}} = \) concentration of the organism) and calculated the incident UV radiation using Beer's law for both a cylindrical and a rectangular reactor. Four different flow regimes were investigated; a completely mixed reactor, several completely mixed reactors in series and two plug flow types. Of the plug flow reactors, one was modelled to operate at a low velocity, thereby inducing very little turbulence and producing stratified flow. The other plug flow model operated at higher flow velocities and therefore more turbulence was generated throughout the system. Results of the study indicated that the hydraulic characteristics of a UV disinfection unit play a significant role in determining its efficiency. The plug flow reactor, which exhibited good radial mixing characteristics, was found to outperform those units which experienced longitudinal
mixing (several perfectly mixed reactors in series) or vertical stratification (plug flow reactor run at a very low flow rate).

Further evidence of the importance of proper mixing within a UV reactor was presented by Severin et al. [1984]. Their experiments utilized a one-lamp continuous flow reactor vessel that was equipped with two impellers which could be operated individually or simultaneously to produce partially or fully mixed conditions. The models derived for this study correctly predicted the disinfection efficiency of a completely mixed UV reactor but did not accurately predict the efficiency of the partially mixed experiments. Theoretical inactivation curves of both completely mixed and perfect plug flow were also calculated and it was demonstrated that in most cases, the perfect plug flow model outperformed that of the completely mixed condition. It was concluded that increased disinfection efficiency would be achieved with increased radial mixing. In addition, longitudinal mixing should be kept to a minimum as this reduces reactor efficiency. However, some longitudinal mixing may be required in order to ensure that radial stratification does not occur.

Previous work conducted by Scheible [1987] on the design of an ultraviolet disinfection unit emphasized the importance of good hydraulics for creating an efficient reactor. He stated that optimum performance would be achieved through perfect plug flow characteristics, that is significant radial mixing with minimal longitudinal mixing.
1.4. Objectives

The proper design of an efficient UV disinfection unit must incorporate several different design criteria. As discussed earlier, previous research has suggested that optimum disinfection performance occurs when flow conditions exhibit intense radial mixing while minimizing longitudinal dispersion within a UV lamp array [Cortelyou et al., 1954, Hass et al., 1979, Blatchley et al., 1995 and Scheible, 1987]. Consequently, a series of design modifications were proposed and experiments were conducted to try and increase the performance of Elsag Bailey’s existing UV disinfection unit. The objectives of this research were:

1) To examine the characteristics of the turbulent flow in an existing UV disinfection unit. This was accomplished using an Acoustic Doppler Velocimeter (ADV) which measures all components of the turbulent velocity. Flow visualization was used to give a qualitative as well as a quantitative interpretation of the mixing regimes existing within the reactor.

2) To design and construct modifications to the existing unit that could improve its performance by enhancing radial mixing. These modifications were required to meet the following design criteria:

i) Maintain or create a minimum level of turbulence down the entire length of the disinfection unit. Blatchley et al. [1995] noted that the lamp array promotes the formation of a uniform velocity profile. The lamps act as ‘flow straighteners’ and will tend to dampen the turbulent flow patterns present within the system. Therefore, it may be necessary to generate mixing along
the entire unit as the turbulence created at the upstream end may quickly
dissipate due to the influence of the lamps.

ii) Minimize the magnitude of the headloss experienced along the length of the
unit. Depending on the design of the wastewater treatment plant, disinfection
units may be placed in series and as a result the headloss of each unit will be
superimposed on the upstream units. The maximum allowable water depth
over the top row of quartz sleeves is approximately 2.5 cm and therefore the
headloss per unit must be kept to a fraction of this.

iii) Ensure that the quartz sleeves remain fully submerged. The layer of fluid
above the lamps serves the purpose of dissipating heat from the lamps,
discourages the formation of residue on the surface of the quartz sleeve and
adds a layer of protection for the plant operators from the UV light.

iv) Select a design that will not be prone to mechanical failure.
2. **Design Alternatives**

The current UV system manufactured by Elsag Bailey consists of an array of UV mercury vapour lamps individually surrounded by cylindrical quartz sleeves. The 2.45 cm (0.96 inches) diameter sleeve serves the dual purpose of protecting the lamp from debris as well as facilitating the transmission of UV energy to the surrounding wastewater. The array is held together in a stainless steel grid and the existing upstream supports swivel so as to assist in lamp cleaning and replacement. During ideal operating conditions, the quartz sleeves are covered with approximately 2.5 centimeters of water and typical water velocities range from 20 cm/s to 40 cm/s.

In order to increase the turbulent mixing throughout the UV rack, it was necessary to design and test several modifications of the existing system. Initially, it was proposed that structural changes be implemented to the upstream end of the rack and as a result, the introductory tests focused on modifying the front end lamp supports. These modifications emphasized the importance of increasing the intensity of the turbulence entering the UV racks. Subsequent designs however, concentrated on generating and maintaining turbulence within the rack. For these trials, stainless steel washers of various sizes were installed over the quartz sleeves of the current UV system design. Table 2-1 presents a listing of the names of the different configurations tested for this study along with a brief description of their geometry. Images of the different rack configurations and washers are found in Figure 2-1. The upstream supports of racks A, B, C, D and the flat plates (racks M and L) are shown horizontal but when attached to the rack, they were positioned
vertically. Also pictured are the different sized washers used in the experiments, and the end supports of racks E and Q.

<table>
<thead>
<tr>
<th>Rack Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Big squares (plate width = 5.1 cm, 4.1 cm x 3 cm square)</td>
</tr>
<tr>
<td>B</td>
<td>Small squares (plate width = 4.7 cm, 3.8 cm x 3 cm square)</td>
</tr>
<tr>
<td>C</td>
<td>Ovals (plate width = 4.76 cm, 8.55 cm² area of one oval)</td>
</tr>
<tr>
<td>D</td>
<td>Circles (plate width = 4.76 cm, 2.86 cm diameter circles)</td>
</tr>
<tr>
<td>E</td>
<td>Current UV system design, swivel supports upstream with rounded bullet inserts</td>
</tr>
<tr>
<td>F</td>
<td>Current UV system design, swivel supports downstream with rounded bullet inserts</td>
</tr>
<tr>
<td>G</td>
<td>4.45 cm Rubber O-rings (1.75 inches outer diameter)</td>
</tr>
<tr>
<td>J</td>
<td>4.45 cm (1.75 inches) washers</td>
</tr>
<tr>
<td>K</td>
<td>5.08 cm (2.0 inches) washers</td>
</tr>
<tr>
<td>L</td>
<td>Metal plate (large) with backwards system</td>
</tr>
<tr>
<td>M</td>
<td>Metal plate (small) with backwards system</td>
</tr>
<tr>
<td>N</td>
<td>3.81 cm (1.5 inches) washers</td>
</tr>
<tr>
<td>O</td>
<td>4.13 cm (1.625 inches) washers</td>
</tr>
<tr>
<td>P</td>
<td>4.76 cm (1.875 inches) washers</td>
</tr>
<tr>
<td>Q</td>
<td>New welded front end (shorter lamps were used)</td>
</tr>
<tr>
<td>R</td>
<td>5.08 cm (2.0 inches) and 3.81 cm (1.5 inches) washers</td>
</tr>
</tbody>
</table>

Table 2-1: Different rack configurations tested: for racks G, J, K, L, M, N, O, and P, the modifications, eg. the washers, were implemented on the original rack (rack E).

Four additional rack modifications not described in Table 2-1 were also tested. Three of these were variations of upstream supports, a 4 cm wide plate support without holes and two sets of cross shaped angled plates. The fourth design alternative consisted of small rubber o-rings of diameter 3.02 cm (1.19 inches) placed on the quartz sleeves. These modifications however, did not produce any significant changes to the flow patterns of the original rack (rack E) and therefore were not investigated further.
Figure 2-1: Rack configurations of upstream rack supports and washers.
3. Experimental Methodology

The three UV supports used throughout this study were supplied by Elsag Bailey. The mercury vapour lamps used in the actual disinfection systems however, were not installed during the experiments. Individual racks consist of a 5 column by 4 row array of 2.45 cm (0.96 inches) diameter quartz sleeves. The sleeves are installed with a horizontal and vertical centreline spacing of 7.62 cm (3 inches) and are arranged parallel to the direction of flow. The original design (Rack E) employs quartz sleeves 1.61 m (63.5 inches) in length. Rack Q however, was constructed with a different front end lamp support and as a result, the length of the quartz sleeves were shortened to 1.56 m (61.6 inches). The racks with the various upstream plate supports, as well as those with the washers, i.e. racks A through P, utilized the original, longer quartz sleeves. The washers used in rack R were placed on the shorter sleeves. For racks A to D, the upstream plate supports were interchangeable as they were fastened and removed via nuts and bolts near the upstream end.

All experiments were conducted in the River Flow Laboratory of the Department of Mechanical and Industrial Engineering at the University of Toronto. The channel measures 38.89 cm (15.31 inches) in width, 46 cm (18.1 inches) in depth and has an approximate length of 12 m. A 14.9 kW (20 hp) pump was used throughout and by opening and closing a series of valves, flow rates of between 0.011 m³/s to 0.067 m³/s were achieved. Flow rates were measured using an elbow meter. This apparatus works on the principle that there is a pressure difference present between the inner and outer radii of a pipe bend when a steady flow is present. The pressure difference is measured.
with a pair of water-filled manometers. The head difference across the pipe bend, $\Delta h$ (in decimal feet), is related to the discharge, $q$ ($\text{ft}^3/\text{s}$) by the following equation:

$$\Delta q = 2.2463 \sqrt{\Delta h}$$  \hspace{1cm} (7)

Throughout all of the experiments, water levels were held constant downstream of the racks at a depth of 29.21 cm (11.5 inches).

3.1. Preliminary Flow Visualization Experiments

In order to gain a better understanding of the flow patterns present in the UV rack, preliminary flow visualization experiments were conducted. The mixing and flow patterns were visualized by making video recordings as a neutrally buoyant tracer (red dye) was injected into the flow. The videos were recorded using a Sony CCD-TR600 camcorder and a JVC HR-S5200U VCR. The flow patterns were backlit by placing two 300 Watt halogen lamps behind the far channel wall. A sheet of Mylar was taped to the backside of the far channel wall to diffuse the light. A schematic of the setup of the video equipment is shown in Figure 3-1.

For the dye to accurately follow the flow, it must be neutrally buoyant. That is, it must be at the same temperature as the water in the channel. To ensure this, water was taken from the channel just prior to each set of experiments and mixed with the powdered dye to produce a neutrally buoyant liquid dye. The red dye was injected through a long thin tube (approximate diameter of 1 mm) at selected spots in the flow as shown in Figure 3-2. The velocity of the dye as it exits the tube is a function of the height of the dye reservoir relative to the water surface. In order to be certain that the dye was entering the flow at the same velocity as the surrounding stream, a series of tests were conducted.
These consisted of filling a 14 mL test-tube with dye and placing it a known distance above the water surface. The height of the dye injection point was also recorded. A stopwatch was used to measure the length of time needed to empty the test-tube and from this a corresponding flow rate and dye exit velocity were calculated. This process was repeated for varying heights of both the dye reservoir and injection point and the corresponding curve of the dye exit velocities was plotted. Therefore, for a specific channel velocity, there is an appropriate reservoir height which will allow the dye to exit at the same velocity as the surrounding fluid. The plot used to determine the dye reservoir heights is found in appendix A, Figure A-1.

Figure 3-1: Video setup used in flow visualization experiments.
For these preliminary flow visualization tests, dye was injected at each of the five positions and this was repeated at three different axial locations as shown in Figure 3-3. The first injection point was placed immediately upstream of the entrance to the rack, another at 1/3 of a rack-length downstream of the rack entrance and one at 2/3 of a rack-length downstream.

![Diagram of rack with injection positions](image)

**Figure 3-2:** The transverse locations (I-V) where dye was injected for the preliminary flow visualization experiments.

For racks A through G, runs were conducted at channel velocities of 20.3 cm/s and 30.9 cm/s. Tests on racks J through R were conducted at velocities of 30.9 cm/s and at their respective maximum operating velocities. At each transverse position, axial location, and velocity, video recordings of approximately 2.5 minutes in length were taken; this process was repeated for all of the racks.
3.2. Acoustic Doppler Velocimeter (ADV) Experiments

In conjunction with the preliminary flow visualization tests, velocity measurements were also conducted on the racks listed in Table 2-1. For these experiments, an Acoustic Doppler Velocimeter (ADV) manufactured by Sontek (San Diego, CA) was used. The ADV is a computerized velocity probe that, when immersed in a flow, is capable of measuring all three turbulent velocity components, $u$, $v$, and $w$, the x-, y-, and z-velocity components, respectively. The probe consists of a central transmitting transducer and three receiving transducers that are oriented around the transmitting transducer at $120^\circ$ intervals. The receiving transducers are angled such that their signals intercept the transmitted beam at a point located approximately 5 cm directly in front of the transmitting transducer (see Figure 3-4). The volume defined by the intersection of the four beams represents the measuring volume. Instantaneous channel velocities are obtained by processing the signals which are received from the scattering of the
transmitted acoustic beams by small suspended particles in the water. The probe used for these experiments was a 3-D side looking probe, chosen because it fits between the closely spaced quartz sleeves in the UV rack.

(a) 
(b) 
(c)

Figure 3-4: Schematics of the ADV probe. (a) Coordinate system of the ADV 3-D side looking probe. (b) Dimensions of the ADV probe. (c) Position of the sampling volume of the ADV down looking probe.

For the experiments, the coordinate system defined by the ADV probe, as shown above, was redefined so that the positive x direction was vertically up, the positive y was directed downstream, and the z direction in the transverse direction (i.e. 90 degrees to the direction of flow). The probe was held in place by a modified equatorial telescope mount and this setup allowed the probe to be accurately positioned. Given the design of the ADV probe and its mount, it was possible to orient the sampling volume at any angle to
the flow direction. Tests were conducted to determine the probe orientation which produced the smallest disturbance to the flow and thus the most accurate results.

With the probe stem held vertical, (i.e. in the y-z plane) the sampling volume can only be rotated in a plane parallel to the direction of flow. For this setup the effect of aiming the probe directly upstream ($\phi = 0^\circ$ to the flow), at a $45^\circ$ angle and at $90^\circ$ angle to the flow was investigated (see Figure 3-5). It was found that $\phi = 90^\circ$ caused the least interference and as a result all velocity measurements were acquired with the probe in this position.

![Figure 3-5: ADV positioned in the channel to test for flow interference at different probe angles.](image)

In addition, it was necessary to determine an adequate duration for the sampling time. Sample times of 1, 5 and 10 minutes were collected and compared and it was determined that a 1 minute duration was sufficient. The sampling rate for all of the experiments was set to the ADV's maximum rate of 25 Hz. Changes in water temperature
produce corresponding changes in the speed of sound in water and in order to account for these effects, the temperature must be entered into the ADV software. Consequently, during each experiment, the temperature of the channel water was closely monitored using a mercury thermometer and/or an Orion Model 140 Conductivity/ Temperature/ Salinity Meter.

It was necessary to sample the velocity at various axial locations along the length of the UV rack in order to accurately represent the velocity variations. Closely spaced sampling points are needed in regions around flow obstacles, such as the washers, to precisely resolve any resulting fluctuations. As a result, for the racks with modified front supports velocity measurements were taken at 9 axial locations within the rack. For the racks with washers, velocity measurements were sampled at 24 axial locations. In all cases, one downstream and two upstream velocity measurements were also taken. These served as reference data for taking into account the deviations in velocities associated with the channel itself. Figure 3-6 and 3-7 illustrate the axial locations at which velocity measurements were made for racks with modified front end supports and for racks with washers.

![Diagram of UV rack with axial locations](image)

**Figure 3-6:** Axial locations of ADV sampling points for racks with modified upstream supports.
At each axial location, velocity measurements were acquired at two transverse positions. Position 1 was midway between the centreline of adjacent vertical and horizontal lamps and position 2 was equidistant from the four quartz sleeves as shown in Figure 3-8. At position 2, the UV intensity is a minimum and as discussed earlier, pathogens trapped along these pathlines will experience reduced radiation dosages. In addition, it is expected that the turbulence intensity will be the smallest at this location and hence, any changes in the minimum turbulence intensity occurring at this central point will reflect corresponding increases/decreases in the average turbulence intensity level. A second measurement location was desired so position 1 was chosen because it is the furthest location from position 2 that can be measured with the ADV aimed 90° to the flow. As mentioned previously, it was found that the measured flow is least disturbed when the ADV probe is aligned perpendicular to the flow and therefore this orientation was maintained throughout the experiments. In total, twelve axial velocity measurements were taken at transverse positions 1 and 2 for racks with modified supports, and 27 axial measurements per position, for those racks with washers.

Figure 3-7: Axial locations of ADV sampling points for racks with washers.
3.3. Quantitative Flow Visualization Experiments

Quantitative flow visualization experiments were completed with racks that utilized the washers and rack Q. For this set of tests, the axial location of the dye injection point was fixed at 5 cm upstream of each set of washers and the camera position and field of view were held constant for all tests. Approximately one minute of video was acquired as dye was injected at each of 4 transverse positions and this was repeated twice per rack, once at each set of washers. The dye injection points are shown in Figure 3-9.

Some of the resulting video images were then digitized using a PC equipped with a frame grabber board (Oculus TCi-Se) and its accompanying software package (TCi-Pro). At each dye injection position, 25 randomly selected images were digitized and then converted using Graphic Workshop software, from color TIF files to grey-scale BMP files. The individual black and white images were each composed of a 320 by 240 pixel array of 8 bit numbers (0 - 255) where a value of zero corresponds to a pixel which is black, and 255 corresponds to one that is white.
Twenty digital images were combined into a single composite image. This composite was formed by comparing corresponding pixels in two images and always setting the grey scale for that particular pixel to the darkest of the two values (i.e. the smaller value). This process was repeated iteratively until twenty images had been combined. The final image is one in which each pixel has a grey scale value that is the darkest value that occurs in any of the twenty images. The composite images produced using this technique are analogous to a long time exposure photograph. The resulting outline of the dye plume is much more distinct in the composite images than in the single images making it easier to make quantitative comparisons between the plumes produced by the different racks.

Video recordings were also used to measure the height of the water flowing over the quartz sleeves. A level ruler, placed near the water surface, was used as a scale marker. For each channel velocity (30 cm/s and the particular rack's maximum velocity) close-up video recordings were taken along the entire length of the rack. The recordings were then analyzed and water heights were measured directly on the video monitor screen.

For each rack it was necessary to determine the velocity at which the top row of quartz sleeves became exposed to the atmosphere. Channel velocity was increased until some section of the upper quartz sleeves were no longer covered with water. The flow rate was then decreased until the sleeves were again fully submerged. This velocity was then recorded as being the maximum at which that particular UV rack could operate safely. Note that the downstream water level was held constant at 29.21 cm in order to maintain the same conditions for all the racks.
Figure 3-9: Dye injection points for the quantitative flow visualization experiments
(a) Side view of channel and dye injection points. (b) Cross-sectional view of channel and injection points. (c) Close up view of injection point 2.
4. Results

4.1. Preliminary Flow Visualization

Figure 4-1, (a) and (b), are a pair of individual digitized images taken during the preliminary flow visualization experiments for rack E with a channel velocity of 30.9 cm/s. Figure 4-1 (a) shows the dye being injected at the upstream end of the rack at transverse position I (see Figure 3-2) and Figure 4-1 (b) shows dye being injected at the same transverse position but at an axial location 1/3 the length of the rack downstream. It is evident from these images that little mixing occurs between the surface and the top row of quartz sleeves. This area is of particular concern because pathogens can become trapped in this upper layer and as a result, may not receive a sufficient dose of UV radiation. These microorganisms are effectively bypassing the lamp array and may not be adequately treated during passage through the system.

![Figure 4-1](image)

Figure 4-1: Images of the preliminary flow visualization experiments for rack E at dye injection point I and a water velocity of 30 cm/s. (a) Entrance to the rack, (b) 50 cm downstream of the rack entrance.

The video recordings of the racks with modified supports (racks A, B, C, D, L and M) confirmed that the modified supports produced enhanced mixing immediately
downstream of the supports. However, the region of enhanced mixing did not extend more than approximately 40 cm downstream of the supports. In addition, the preliminary flow visualization experiments demonstrated that the parallel quartz sleeves channel the flow directly downstream and effectively dampen any initial disturbances. As a result, it was evident that it would be necessary to employ modifications which would help generate and maintain turbulence throughout the rack. For the racks with washers, the mixing at the upstream end is either equal to or slightly reduced compared to the mixing produced by rack E but there is clearly an increase in mixing throughout the rest of the system. From these preliminary tests, some of the upstream modifications were eliminated from further testing (racks C and D) as they did not demonstrate a significant improvement in mixing when compared to rack E.

4.2. Maximum Operating Velocity

Under normal operating conditions it is a requirement that the quartz sleeves remain completely covered by a layer of water. This layer serves to keep the quartz sleeves from overheating and it helps prevent the premature build-up of scum on the lamps. In addition, the water provides a barrier that protects the system operators from the ultraviolet light.

It was observed that at a given velocity, the water level over the sleeves varies as a function of axial position along the UV rack. The variations in water level may be small for slow velocities (10 to 20 cm/s), but they become large as the velocity or the blockage are increased. The blockage $B_1$, is defined as the ratio of total cross-sectional area of the
obstruction (rack supports or washers plus sleeves) to the total cross-sectional area of the channel at a depth of flow of 29.21 cm (11.5 inches). It is given by,

\[ B_t = \frac{A_b}{A_T} \]  \hspace{1cm} (8)

where \( A_b \) is the cross-sectional area of the obstruction and \( A_T \) is the total channel area.

For example, rack K which was equipped with 5.08 cm diameter washers has a blockage of \( B=35.9\% \) and can only operate at velocities up to 36 cm/s. At the larger velocities the upper row of quartz sleeves becomes exposed to the atmosphere. As a result, maintaining an acceptable water height above the sleeves places a restriction on the maximum velocity at which a given configuration can operate. Maximum velocities were measured for the racks with washers and for rack Q. The racks with modified upstream supports however, were only tested at channel velocities up to 50 cm/s, because at the time of these early tests it was believed that this upper velocity was sufficiently high for normal operating conditions. In Table 4-1, the maximum (or highest tested) velocities and the blockage values of each rack are listed.

From these blockage values, it can be seen that for the racks with washers there is a direct correlation between blockage and maximum operating velocity. As the channel blockage is increased, from 20.2\% to 35.9\%, for racks N and K respectively, the maximum operating velocity decreases from 59 cm/s to 36 cm/s. The geometry of the blockage also influences the maximum allowable velocity. For example, rack A (modified upstream support) had a blockage of 46\% and was still operational at 50 cm/s whereas rack K (washers) with a blockage of 35.9\% had a maximum operating velocity of 36 cm/s.
<table>
<thead>
<tr>
<th>Rack Name</th>
<th>Maximum Velocity (cm/s)</th>
<th>Blockage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>tested up to 50 cm/s*</td>
<td>46.8</td>
</tr>
<tr>
<td>B</td>
<td>tested up to 50 cm/s*</td>
<td>43.1</td>
</tr>
<tr>
<td>G</td>
<td>tested up to 50 cm/s*</td>
<td>27.5</td>
</tr>
<tr>
<td>L</td>
<td>tested up to 50 cm/s*</td>
<td>40.0</td>
</tr>
<tr>
<td>M</td>
<td>tested up to 50 cm/s*</td>
<td>35.0</td>
</tr>
<tr>
<td>E</td>
<td>tested up to 50 cm/s*</td>
<td>28.1</td>
</tr>
<tr>
<td>N (3.81 cm)</td>
<td>59</td>
<td>20.2</td>
</tr>
<tr>
<td>O (4.13 cm)</td>
<td>54</td>
<td>23.7</td>
</tr>
<tr>
<td>J (4.45 cm)</td>
<td>50</td>
<td>27.5</td>
</tr>
<tr>
<td>P (4.76 cm)</td>
<td>49</td>
<td>31.5</td>
</tr>
<tr>
<td>K (5.08 cm)</td>
<td>36</td>
<td>35.9</td>
</tr>
<tr>
<td>Q (new welded front end)</td>
<td>52</td>
<td>25.9</td>
</tr>
<tr>
<td>R (5.08 cm and 3.81 cm)</td>
<td>41</td>
<td>35.9</td>
</tr>
</tbody>
</table>

* Rack configurations still operational at 50 cm/s; untested at higher velocities.

Table 4-1: Values for the maximum operating velocities and rack blockages.

4.3. Water Surface Profiles

Under ideal operating conditions, the depth of water over the uppermost sleeves is equal to approximately 2 cm along the entire length of the rack. Figure 4-2 (a) shows a plot of the water level data collected for rack E measured at a channel velocity of 30 cm/s.

In the water level figures, a water surface elevation of -1 cm corresponds to the top of the uppermost sleeves. Looking closely at the water profile for rack E, there is a dip of approximately 0.7 cm in water level near the upstream end of the rack which can be attributed to the constriction caused by the lamp supports. The water height then quickly recovers and remains relatively constant until reaching the downstream end of the rack at which point there is a 0.4 cm dip in water height due to the constriction caused by the rear supports. Further downstream past the end of the rack, the water level fully recovers to
its upstream depth indicating that there is no detectable head loss through this rack at a velocity of 30 cm/s..

In Figure 4-2 (b) the data for rack J is plotted and it can be seen that the addition of washers serves to greatly modify the water surface profile. The initial dip at the upstream end has been reduced compared to rack E and now there are two distinct decreases in water level at approximately 75 cm and 145 cm. These fluctuations are caused by the constrictions associated with the washers. The last dip near the rear of rack J is also due to the end supports. In contrast to rack E, rack J experiences a head loss through the rack of approximately 0.6 cm.

Figure 4-3 (a) and (b) shows the same two racks (E and J) at a velocity of 50 cm/s. As mentioned previously, the fluctuations in water level are dependent on rack configuration as well as channel velocity and it is evident that the increase in flow has exaggerated those water level drops observed at 30 cm/s. For rack E at 50 cm/s, the initial dip is approximately 2.2 cm compared to 0.7 cm at 30 cm/s, and at the exit to the rack, there is a dip of 2 cm at 50 cm/s versus 0.6 cm at 30 cm/s. The same comparisons can be drawn for rack J where the initial dip at 30 cm/s is approximately 0.3 cm and 1.3 cm for 50 cm/s. Similar results were obtained for the other racks tested. (See appendix C for plots of the water surface profiles in all the racks.)
Figure 4-2: Water surface profiles at 30 cm/s, a water surface elevation of -1 cm corresponds to the top of the uppermost quartz sleeves. The rack entrance is at $y = 0$ cm and the exit is at $y = 170$ cm. (a) Rack E. (b) Rack J, washers are positioned at 47 cm and 113 cm downstream of rack entrance.
Figure 4-3: Water surface profiles at 50 cm/s, a water surface elevation of -1 cm corresponds to the top of the uppermost quartz sleeves. The rack entrance is at y = 0 cm and the exit is at y = 170 cm. (a) Rack E. (b) Rack J, washers are positioned at 47 cm and 113 cm downstream of rack entrance.
4.4. Velocity Distributions

In Figure 4-4, the three mean velocity components are plotted as a function of y, the axial position for rack E at a channel velocity of 30 cm/s and at transverse position 2. It is evident from these plots that the UV rack support has a significant effect on the flow field. The first two data points upstream of the UV rack show the velocities entering the rack; almost immediately downstream of the rack entrance, there are noticeable differences in all three velocity components. The variations in all three components of the mean velocity indicate that the flow field along the rack is quite complex.

The x- and z-velocity components had small variations along the rack, ±1 cm/s and ±2 cm/s respectively. The axial velocity (y-component) increases abruptly at the entrance to the rack due to the constriction caused by the supports. The quartz sleeves provide a blockage B = 8.9% and therefore we would expect the average velocity inside the rack to be approximately 11% higher than the upstream value. This is consistent with Figure 4-4 where the mean velocity varies from 36 to 37 cm/s at approximately 50 cm to 150 cm downstream of the rack entrance. The data point located at y=250 cm, was sampled in order to compare downstream flow velocities with those entering the UV rack.
Figure 4-4: Mean velocity components versus y at transverse position 2 for rack E at a channel velocity of 30 cm/s. Rack entrance at y=0 cm, exit at y=160 cm. (a) x-component. (b) y-component. (c) z-component.

In contrast, the racks equipped with washers reveal flow velocity patterns which differ significantly from those found in rack E. Figure 4-5 shows plots of the mean velocity for rack P collected at a channel velocity of 30 cm/s and at transverse position 2. The most apparent difference in these plots compared to Figure 4-4 are the pronounced peaks in the y-velocity located at 50 and 115 cm downstream of the rack entrance, corresponding to the axial locations of the washers. The y-component of velocity increases by approximately 55% at the first set of washers (the difference between the peak y-velocity and the y-velocity immediately downstream of the rack entrance). Small variations in the x and z velocities are also observed at the washer locations.
Figure 4-5: Velocity versus $y$ measured at transverse position 2 for rack P at a channel velocity of 30 cm/s. Rack entrance at $y=0$ cm, exit at $y=160$ cm. (a) x-component. (b) y-component. (c) z-component.

A rack with two different diameter washers was investigated because it was felt that this combination may lead to better overall mixing characteristics compared to racks with uniform washers. Rack R had 5.08 cm diameter washers positioned at $y=45$ cm and 3.81 cm diameter washers at $y=105$ cm downstream of the rack entrance. Mean velocity as a function of $y$ for rack R are plotted in Figure 4-6 and as before, the plots are characterized by the large fluctuations near the washers. The y-component upstream peak however, is distinctly larger in magnitude than the downstream, as a result of the difference in washer size (5.08 cm upstream versus 3.81 cm for the downstream washer).
Figure 4-6: Velocity versus y measured at transverse position 2 for rack R at a channel velocity of 30 cm/s. Rack entrance at y=0 cm, exit at y=160 cm. (a) x-component. (b) y-component. (c) z-component.
5. Analysis

5.1. Turbulence Intensity and Standard Deviation plots

The velocity data collected by the ADV can be further analyzed to reveal more about the mixing processes present in the UV racks. Displayed in Figure 5-1 is a typical turbulent velocity time series. If velocity data is acquired for a length of time $\tau$, then a mean value for the velocity can be calculated using the following definition:

$$\overline{V} = \frac{1}{T} \int_{0}^{T} V(t) \, dt$$  \hspace{1cm} (9)

where $\tau$ should be longer than the time scale of the fluctuating components. The fluctuating or turbulent component of the velocity is given by,

$$V' = V(t) - \overline{V}.$$  \hspace{1cm} (10)

![Figure 5-1: A typical turbulent velocity time series.](image-url)
By definition, the fluctuating component of the velocity has a mean of zero. The mean square value of the fluctuating velocity is given by,

\[ \overline{V'^2} = \frac{1}{T} \int_0^T V'^2 \, dt. \]  

(11)

The root mean square (rms) or standard deviation of the fluctuating velocity is given by \( \sqrt{\overline{V'^2}} \). A quantitative measure of the intensity of the turbulence in a particular flow is defined as,

\[ I_T = \frac{\sqrt{\overline{V'^2}}}{\bar{V}} \]  

(12)

where the intensity \( I_T \) can be expressed as a decimal or a percentage. The more intense turbulent flow the average magnitude of \( V' \) is larger and more kinetic energy carried in the fluctuating velocity field. In a typical channel flow \( I_T \) will be equal to approximately 5%. More intense turbulent flow fields will be associated with greater mixing in all three coordinate directions and therefore the intensity can be used as a quantitative indicator of the mixing effectiveness of a particular flow field.

In Figure 5-2 the curves of turbulence intensity versus the axial distance for racks E and Q are shown and the plots are almost identical. In both racks, an increase in intensity is observed immediately downstream of the rack entrance due to the turbulence created by the upstream supports. This turbulence decays quite rapidly with downstream distance and within approximately 60 cm of the rack entrance the intensity returns to the value observed outside the rack. Similar results are also observed for these racks at
transverse position 1. It is obvious that with these two configurations, the turbulence generated near the entrance is not sustained throughout the rack.

Figure 5-2: Turbulence intensity versus axial distance $y$ for a channel velocity of 30 cm/s at transverse position 2. $y=0$ cm is the entrance to the rack. (a) Rack E. (b) Rack Q.
The turbulence intensity curve for rack P is shown plotted in Figure 5-3. There are three turbulence intensity peaks compared to the single peak observed for racks E and Q. The first peak in rack P due to the upstream supports is smaller in magnitude when compared to the single peak in rack E. However, the peaks associated with the washers on rack P are of similar magnitude to the single peak in rack E. Results for rack P at position 1 were similar to those at position 2, except with slightly higher peaks.

Figure 5-3: Turbulence intensity as a function of the axial distance y for Rack P at a channel velocity of 30 cm/s, at transverse position 2.

Table 5-1 presents the turbulence intensity data calculated for racks E, Q and for the racks with washers. The upper portion of the table is the average turbulence intensity. This quantity was computed for the region bounded by the entrance and exit of the rack.
(i.e. the two upstream and one downstream points were not used in these results). The average intensity was calculated by the following integral expression,

\[ A_i = \frac{1}{l} \int_{x_0}^{x_f} I_T \, dx \quad (13) \]

where \( x_0 \) is the position of the first velocity sampling point immediately downstream of the rack entrance, \( x_f \) is the last velocity sampling point within the rack and \( l \) is the length of the rack. Looking closely at the data presented for a channel velocity of 30 cm/s in Table 5-1, it is evident that as washer size increases there is a corresponding increase in the average turbulence intensity. In comparison to racks E and Q, the racks with washers consistently show increased average turbulence intensity values, with the largest difference occurring between racks K and E.

In the lower portion of Table 5-1 the maximum peaks from the turbulence intensity curves are tabulated. The magnitude of the peaks increases with increasing washer size. At transverse position 2, both the average and peak intensity are significantly lower than the values observed at position 1. For example, for rack K at a channel velocity of 30 cm/s, the peak intensity at position 2 is 0.188 and at position 1 it is 0.272. These differences clearly demonstrate that within the wakes created by the washers and upstream supports there are rapid spatial variations in the turbulent flow field.
### Average Turbulence Intensity for racks with washers and racks E and Q

<table>
<thead>
<tr>
<th>Channel Velocity</th>
<th>E (original)</th>
<th>N (1.5&quot;)</th>
<th>O (1.625&quot;)</th>
<th>J (1.75&quot;)</th>
<th>P (1.875&quot;)</th>
<th>K (2&quot;)</th>
<th>Q (new front)</th>
<th>R (1.5&quot;, 2.0&quot;)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 cm/s Position 1</td>
<td>0.070</td>
<td>0.083</td>
<td>0.089</td>
<td>0.099</td>
<td>0.121</td>
<td>0.131</td>
<td>0.077</td>
<td>0.120</td>
</tr>
<tr>
<td>30 cm/s Position 2</td>
<td>0.066</td>
<td>0.067</td>
<td>0.073</td>
<td>0.080</td>
<td>0.094</td>
<td>0.105</td>
<td>0.074</td>
<td>0.113</td>
</tr>
<tr>
<td>Vmax Position 1</td>
<td>0.064</td>
<td>0.089</td>
<td>0.094</td>
<td>0.103</td>
<td>0.127</td>
<td>0.134</td>
<td>0.079</td>
<td>0.123</td>
</tr>
<tr>
<td>Vmax Position 2</td>
<td>0.059</td>
<td>0.069</td>
<td>0.078</td>
<td>0.082</td>
<td>0.108</td>
<td>0.107</td>
<td>0.086</td>
<td>0.119</td>
</tr>
</tbody>
</table>

| Vmax (cm/s) | 50 | 59 | 54 | 50 | 49 | 36 | 52.8 | 41.8 |

### Maximum Peak of Turbulence Intensity curve

<table>
<thead>
<tr>
<th>Channel Velocity</th>
<th>E (original)</th>
<th>N (1.5&quot;)</th>
<th>O (1.625&quot;)</th>
<th>J (1.75&quot;)</th>
<th>P (1.875&quot;)</th>
<th>K (2&quot;)</th>
<th>Q (new front)</th>
<th>R (1.5&quot;, 2.0&quot;)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 cm/s Position 1</td>
<td>0.217</td>
<td>0.205</td>
<td>0.186</td>
<td>0.217</td>
<td>0.285</td>
<td>0.272</td>
<td>0.149</td>
<td>0.295</td>
</tr>
<tr>
<td>30 cm/s Position 2</td>
<td>0.151</td>
<td>0.105</td>
<td>0.101</td>
<td>0.114</td>
<td>0.189</td>
<td>0.188</td>
<td>0.163</td>
<td>0.211</td>
</tr>
<tr>
<td>Vmax Position 1</td>
<td>0.249</td>
<td>0.243</td>
<td>0.261</td>
<td>0.267</td>
<td>0.314</td>
<td>0.321</td>
<td>0.164</td>
<td>0.333</td>
</tr>
<tr>
<td>Vmax Position 2</td>
<td>0.124</td>
<td>0.115</td>
<td>0.115</td>
<td>0.132</td>
<td>0.212</td>
<td>0.193</td>
<td>0.246</td>
<td>0.231</td>
</tr>
</tbody>
</table>

| Vmax (cm/s) | 50 | 59 | 54 | 50 | 49 | 36 | 52.8 | 41.8 |

Table 5-1: Area under and maximum peaks of the turbulence intensity curves for racks with washers and racks E and Q.

As the mean velocity is increased, the effect of the washers becomes more pronounced, as seen by comparing the plots of rms velocities for racks E and P at 30 cm/s and 50 cm/s. The maximum velocity of 49 cm/s for rack P is slightly less than that of rack E (50 cm/s) but this difference is small enough (2% difference) that a comparison is still valid. Shown below in Figure 5-4 (a) and (b) is rack E at position two with a mean velocity of 30 cm/s and 50 cm/s respectively. As expected, there are increases in the rms velocities measured immediately downstream of the rack entrance. The peaks in the x, y and z directions for the 50 cm/s plots when compared to the 30 cm/s plots have increased by 34%, 54% and 8% respectively. For rack P, Figure 5-5 (a) and (b), the increase in peak levels are even more significant. Increases of 99%, 81% and 57% were observed for the three velocity components.
Figure 5-4: RMS velocities at position 2 for rack E. Rack entrance at y=0 cm. (a) Channel velocity 30 cm/s. (b) Channel velocity 50 cm/s.
Figure 5-5: RMS velocities at position 2 for rack P. Rack entrance at y=0 cm. (a) Channel velocity of 30 cm/s. (b) Channel velocity of 49 cm/s.
5.2. Quantitative Flow Visualization Tests

The composite images created from the quantitative flow visualization tests provide an objective method for assessing the mixing characteristics found within the flow. Figure 5-6 (a) is a single digitized image of rack K at a channel velocity of 30 cm/s. Figure 5-6 (b) is also of rack K but this time 20 images have been combined so as to create this composite image. It is clear that in the composite image the boundaries of the plume are much more distinct than in the single image and this allows the plume spreading rate to be measured accurately.

Figure 5-7 (a) and (b) are composite images of racks Q and K respectively, at a mean velocity of 30 cm/s. Both images were taken at 108 cm downstream of the rack entrance and the dye was injected at point 1 (see Figure 3-9). In Figure 5-7 (a), it is evident that the plume spreads slowly in rack Q. The lower edge of the plume does not even spread to the adjacent lower quartz sleeve. In sharp contrast, Figure 5-7 (b) shows that the plume within rack K spreads much more quickly and is even observed to spread beyond the lower edge of the adjacent lower lamp.

Visual comparison of the composite images indicated that there was a qualitative difference between the mixing in the racks. In order to obtain a quantitative measure of plume mixing however, a detailed analysis of the composite images was completed. In Figure 5-8 is a schematic of a rack with washers illustrating the method used to obtain the plume spreading rate.
Figure 5-6: Dye plume in Rack K at a channel velocity of 30 cm/s. Axis labels are pixel numbers. (a) Single image. (b) Composite image. (20 images combined)
Figure 5-7: Composite images at a channel velocity of 30 cm/s, 108 cm downstream of rack entrance at dye injection point 1. Axis labels are pixel numbers. (a) Rack Q. (b) Rack K.
Figure 5-8: Schematic of plume spreading measurements.

- - - - - - - = points sampled along the plume boundary
----- = linear regression line of best fit
---------- = line fit through the first and last sampling points

The approximate limits of the plume were identified by running a Matlab program (mathematical analysis software) which displays the composite image on the computer screen. By positioning the mouse along the edge of the plume and clicking at the various sampling points, an outline of the upper and lower edges of the plume was created. Lines calculated by linear regression analysis were drawn through these data points and the resulting slopes of the upper and lower plume boundaries give a measure of the spread of the plume. The total slope, $\Psi$, was calculated by adding the magnitudes of the two slopes. A second method of calculating the spreading rate used a pair of lines drawn only the first and last points for each boundary. The slopes of these lines were then calculated and the total slope defined in this manner was called $\Phi$. Results for racks Q, N, J, K and R at 30
cm/s are displayed in the first section of Table 5-2. As expected, the slopes derived from
the composite images show that the plume has spread significantly faster in rack K than
for rack Q. Slopes $\Psi$ and $\Phi$ for rack K are 0.285 and 0.341, as compared to 0.193 and
0.243 for rack Q. Racks N, J and R also show increases in the rate of spreading of the
plumes when compared to rack Q.

<table>
<thead>
<tr>
<th>Position</th>
<th>Rack</th>
<th>Line of best fit</th>
<th>End points</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>top slope</td>
<td>bottom slope</td>
</tr>
<tr>
<td>Q - new front end</td>
<td>-0.135</td>
<td>0.058</td>
<td>0.193</td>
</tr>
<tr>
<td>1/3 downsteam N - 1.5&quot;</td>
<td>-0.122</td>
<td>0.088</td>
<td>0.210</td>
</tr>
<tr>
<td>middle of 4 J - 1.75&quot;</td>
<td>-0.117</td>
<td>0.133</td>
<td>0.249</td>
</tr>
<tr>
<td>lights K - 2&quot;</td>
<td>-0.136</td>
<td>0.148</td>
<td>0.285</td>
</tr>
<tr>
<td>position 1 R - 1.5&quot; &amp; 2&quot;</td>
<td>-0.116</td>
<td>0.167</td>
<td>0.283</td>
</tr>
<tr>
<td>Q - new front end</td>
<td>-0.135</td>
<td>0.098</td>
<td>0.233</td>
</tr>
<tr>
<td>1/3 downsteam N - 1.5&quot;</td>
<td>-0.139</td>
<td>0.187</td>
<td>0.326</td>
</tr>
<tr>
<td>close to lamps J - 1.75&quot;</td>
<td>-0.142</td>
<td>0.182</td>
<td>0.323</td>
</tr>
<tr>
<td>position 2 K - 2&quot;</td>
<td>-0.176</td>
<td>0.256</td>
<td>0.432</td>
</tr>
<tr>
<td>R - 1.5&quot; &amp; 2&quot;</td>
<td>-0.094</td>
<td>0.318</td>
<td>0.413</td>
</tr>
</tbody>
</table>

Table 5-2: Plume spreading calculations for racks at a channel velocity of 30 cm/s. $\Psi$ - plume spread calculated from the slope of the linear regression lines of best fit. $\Phi$ - plume spread calculated from the slopes of the first and last sampling points. (Complete results of plume spreading are found in appendix A, Table A-4)

Similar results were obtained when analyzing the plume spread for injection point 2
immediately adjacent to the lamps. Figure 5-9 (a) and (b) are of racks Q and K with the
injection point at position 2 (see Figure 3-9) and a channel velocity of 30 cm/s. In these
images, the differences in the plume spreading rate are significant. In rack Q, the dye is
seen in between the top two lamps but the plume is narrow and is does not spread down
to the adjacent lower lamp. In contrast, the plume in rack K quickly reaches the adjacent
lower lamp and some dye is also visible in the flow between the top lamps. Calculation of
the slopes quantifies these differences as slopes $\Psi$ and $\Phi$ for rack Q are 0.233 and 0.253
versus 0.432 and 0.476 for rack K. From Table 5-2, it is observed that there is a consistent increase in plume spreading (i.e. increases in slopes) as washer diameter increases. From the analysis conducted, it was observed that the two different methods of computing the slopes resulted in similar slope calculations with a maximum difference of approximately 20%.

As mentioned earlier, an area of concern is the upper layer of water covering the top lamps as it is important to ensure adequate mixing within this region. Figure 5-10 (a) and (b) are composite images of rack Q and rack K taken at position 3 (see Figure 3-9) at a velocity of 30 cm/s. In rack Q, the dye exits from the injection point and remains trapped near the surface and no dye mixes below the top lamp. In sharp contrast, in rack K, the dye is seen dispersing below the top lamp indicating that the fluid near the free surface is being mixed much more effectively than in rack Q (this data is found in appendix A, Table A-4).
Figure 5-9: Composite images at a channel velocity of 30 cm/s at dye injection point 2. Axis labels are pixel numbers. (a) Rack Q. (b) Rack K.
Figure 5-10: Composite images at a channel velocity of 30 cm/s at dye injection point 3. Axis labels are pixel numbers. (a) Rack Q. (b) Rack K.
5.3. Residence Times

While it is important to monitor the changes in the mixing characteristics throughout the UV disinfection unit, it is also imperative to observe the changes that occur to the residence time of particles within the reactor. The velocity distribution data presented in section 4.4 can be analyzed to provide an estimate of the total time a pathogen would take to traverse the UV unit. If one assumes that a particle moving downstream from axial measuring point 1 to point 2 has a velocity equal to the average of the velocities at both 1 and 2 then the time needed to cross this distance is given by:

\[
\Delta t_{1\rightarrow 2} = \frac{2(d_2-d_1)}{(V_1+V_2)}
\]

where \(\Delta t_{1\rightarrow 2}\) is the time to go from position 1 to 2, \(d_1\) and \(d_2\) are the downstream axial locations of positions 1 and 2, and \(V_1\) and \(V_2\) are the velocities at these positions. By calculating all time intervals and summing over the entire range of internal ADV axial measuring positions it is possible to estimate the total residence time. Table 5-3 lists the residence times for the racks with washers and racks E and Q at position 2 and at a channel velocity of 30 cm/s. The calculated times show that there are decreases from 3.5% to 8.2% for the racks with washers as compared to rack E. Therefore, the advantages of increased mixing experienced due to the washers may be partially or completely offset by the decrease in residence times. However, since the increases in turbulence are quite large in comparison to the small decreases in residence time, it is likely that the net result will be an increase in the applied dosage and hence an improvement in disinfection performance.
<table>
<thead>
<tr>
<th>Channel Velocity</th>
<th>E (original)</th>
<th>N (1.5&quot;)</th>
<th>O (1.625&quot;)</th>
<th>J (1.75&quot;)</th>
<th>P (1.875&quot;)</th>
<th>K (2&quot;)</th>
<th>Q (new front)</th>
<th>R (1.5&quot;, 2.0&quot;)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 cm/s Position 1</td>
<td>4.03</td>
<td>3.98</td>
<td>3.85</td>
<td>3.78</td>
<td>3.93</td>
<td>3.89</td>
<td>4.00</td>
<td>3.89</td>
</tr>
<tr>
<td>30 cm/s Position 2</td>
<td>4.01</td>
<td>3.87</td>
<td>3.72</td>
<td>3.67</td>
<td>3.69</td>
<td>3.68</td>
<td>3.96</td>
<td>3.73</td>
</tr>
</tbody>
</table>

Table 5-3: Residence times for racks with washers and for racks E and Q with a lamp length of 1.47 m.
6. Conclusions

The properties of the flow field present in a UV disinfection reactor are an important factor in their design. As pathogens are transported through the reactors, they will encounter fluctuating magnitudes of both UV intensity and flow velocities and it is vital that the particles receive a sufficient UV dosage in order to ensure effective treatment of the water. Some areas of decreased UV exposure occur along the centreline between the lamps and at the uppermost layer of water above the lamps. In these areas, it is imperative that mixing occur to transport the pathogens to areas of greater UV intensity. As a result, hydraulic tests were conducted on an existing UV disinfection unit (rack E) manufactured by Elsag Bailey (Canada) Inc. to quantify some of its flow characteristics. The existing system was then modified by either altering the upstream supports and/or by fastening various sized washers along the quartz sleeves.

One important factor to consider regarding the proposed design modifications is that the dose of UV radiation received by a pathogen is dependent on both transverse mixing and mean residence time. The transport of microorganisms to areas of increased UV intensity can be facilitated by enhancing transverse mixing and this may produce a corresponding increase in UV dosage. For a given flow rate, the average turbulence intensity can be increased by increasing the mean velocity (i.e. reducing the cross-sectional area) or by modifying the rack (i.e. installing the washers). Installation of the washers produced larger average turbulence intensities and possibly an increase in the UV dosage. However, the washers constrict the flow and reduce the mean residence time which will decrease the UV dosage. As a result, the disinfection performance of a particular rack
design will depend on determining the optimal values for both the average turbulence intensity and the mean residence time.

6.1. Summary of Results

For racks with modified upstream supports it was observed that there was significant turbulence created near the entrance of the rack. However, these effects were discovered to dissipate rapidly with increasing downstream axial distance. Consequently, washers were fastened to the quartz sleeves in an attempt to generate turbulence throughout the rack. Analysis of the plots of the turbulence intensity show that the washers indeed generate and maintain an increased level of turbulence. In Table 6-1, the values of the average turbulence intensity are compared to the value for the original design, rack E (i.e. the average turbulence intensities have been non-dimensionalized by dividing by the average turbulence intensity in rack E). All of the racks with washers produced flows with higher turbulence intensities. For example rack K produced average turbulence intensities at positions 1 and 2 that were 1.9 and 1.6 times larger than the corresponding values for rack E. In addition, rack Q with the modified front end produced average turbulence intensities that were approximately 1.1 times larger than the values for rack E.

<table>
<thead>
<tr>
<th>Channel Velocity</th>
<th>E (original)</th>
<th>N (1.5&quot;)</th>
<th>O (1.625&quot;)</th>
<th>J (1.75&quot;)</th>
<th>P (1.875&quot;)</th>
<th>K (2&quot;)</th>
<th>Q (new front)</th>
<th>R (1.5&quot;, 2.0&quot;)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 cm/s Position 1</td>
<td>1.000</td>
<td>1.186</td>
<td>1.283</td>
<td>1.422</td>
<td>1.745</td>
<td>1.878</td>
<td>1.103</td>
<td>1.723</td>
</tr>
<tr>
<td>30 cm/s Position 2</td>
<td>1.000</td>
<td>1.007</td>
<td>1.103</td>
<td>1.211</td>
<td>1.428</td>
<td>1.590</td>
<td>1.122</td>
<td>1.704</td>
</tr>
</tbody>
</table>

Table 6-1: Non-dimensionalized average turbulence intensity data for racks with washers and racks E and Q at a channel velocity of 30 cm/s and at positions 1 and 2. All racks have been non-dimensionalized with respect to rack E.
The data collected during the quantitative flow visualization tests further emphasizes the increased mixing produced by the racks with washers. Table 6-2 summarizes the plume spreading rates, non-dimensionalized by the values observed for rack Q. As expected, the largest differences occur at dye injection points located near the lamps. At these positions, the dye spreads approximately two times faster in rack K than in rack Q at this position.

### Table 6-2: Non-dimensionalized plume spreading rates at a channel velocity of 30 cm/s. All values have been non-dimensionalized with respect to rack Q. \( \Psi_0 \) is the spreading rate of rack Q.

<table>
<thead>
<tr>
<th>Location</th>
<th>Rack</th>
<th>( \Psi/\Psi_0 )</th>
<th>Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/3 downstream of the rack</td>
<td>Q - new front end</td>
<td>1.000</td>
<td>1</td>
</tr>
<tr>
<td>entrance, in the middle of the lights</td>
<td>K - 2&quot;</td>
<td>1.291</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>R - 1.5&quot; &amp; 2&quot;</td>
<td>1.469</td>
<td>1</td>
</tr>
<tr>
<td>2/3 downstream of rack entrance, in the middle of the lights</td>
<td>Q - new front end</td>
<td>1.000</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>N - 1.5&quot;</td>
<td>1.110</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>K - 2&quot;</td>
<td>2.075</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>R - 1.5&quot; &amp; 2&quot;</td>
<td>1.634</td>
<td>1</td>
</tr>
<tr>
<td>1/3 downstream of the rack</td>
<td>Q - new front end</td>
<td>1.000</td>
<td>2</td>
</tr>
<tr>
<td>entrance, very close to the lights</td>
<td>J - 1.75&quot;</td>
<td>1.384</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>K - 2&quot;</td>
<td>1.849</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>R - 1.5&quot; &amp; 2&quot;</td>
<td>1.767</td>
<td>2</td>
</tr>
<tr>
<td>1/3 downstream of rack entrance, very close to the lamps</td>
<td>Q - new front end</td>
<td>1.000</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>N - 1.5&quot;</td>
<td>1.042</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>K - 2&quot;</td>
<td>2.055</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>R - 1.5&quot; &amp; 2&quot;</td>
<td>1.345</td>
<td>2</td>
</tr>
</tbody>
</table>

As mentioned previously, it is important to maintain a high level of transverse mixing throughout the UV rack without substantially decreasing residence times. Data collected for the racks with washers and racks E and Q at position 2 with a channel velocity of 30 cm/s is presented in Table 6-3 and shows that there are decreases in
residence times from 3.5% to 8.2% (average decrease of 7.1% for all the racks with washers) for the racks with washers compared to rack E. Thus the increase in mixing may be partially or completely offset by the decrease in residence time. However, since the increase in turbulence is quite large in comparison to the small decrease in residence time, it is likely that the net result will be an increase in the dose and hence an improvement in disinfection performance. The bioassays to be conducted at Elsag Bailey in the near future will hopefully confirm this hypothesis.

<table>
<thead>
<tr>
<th>Channel Velocity</th>
<th>E (original)</th>
<th>N (1.5&quot;)</th>
<th>O (1.625&quot;)</th>
<th>J (1.75&quot;)</th>
<th>P (1.875&quot;)</th>
<th>K (2&quot;)</th>
<th>Q (new front)</th>
<th>R (1.5&quot;, 2.0&quot;)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 cm/s Position 1</td>
<td>1.000</td>
<td>0.988</td>
<td>0.956</td>
<td>0.938</td>
<td>0.974</td>
<td>0.965</td>
<td>0.992</td>
<td>0.965</td>
</tr>
<tr>
<td>30 cm/s Position 2</td>
<td>1.000</td>
<td>0.965</td>
<td>0.927</td>
<td>0.915</td>
<td>0.920</td>
<td>0.918</td>
<td>0.986</td>
<td>0.928</td>
</tr>
</tbody>
</table>

Table 6-3: Non-dimensionalized residence times for racks with washers and racks E and Q at a channel velocity of 30 cm/s and at positions 1 and 2. All racks have been non-dimensionalized with respect to rack E.
7. **Recommendations**

The data presented in Table 7-1 were collected from the wastewater treatment plants which utilize UV disinfection units manufactured by Elsag Bailey. It is noteworthy that 72% of the plants operate at channel velocities less than 30 cm/s and that 98% operate at velocities less than 47 cm/s. This has important design implications because, while larger washers produce better transverse mixing (i.e. higher turbulence intensities), racks with larger washers also have lower maximum operating velocities.

<table>
<thead>
<tr>
<th>Velocity (cm/s)</th>
<th>Frequency</th>
<th>Cumulative %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.44</td>
<td>1</td>
<td>.86%</td>
</tr>
<tr>
<td>7.07</td>
<td>10</td>
<td>9.48%</td>
</tr>
<tr>
<td>12.70</td>
<td>14</td>
<td>21.55%</td>
</tr>
<tr>
<td>18.33</td>
<td>28</td>
<td>45.69%</td>
</tr>
<tr>
<td>23.96</td>
<td>24</td>
<td>66.38%</td>
</tr>
<tr>
<td>29.59</td>
<td>6</td>
<td>71.55%</td>
</tr>
<tr>
<td>35.22</td>
<td>5</td>
<td>75.86%</td>
</tr>
<tr>
<td>40.85</td>
<td>21</td>
<td>93.97%</td>
</tr>
<tr>
<td>46.48</td>
<td>5</td>
<td>98.28%</td>
</tr>
<tr>
<td>52.11</td>
<td>1</td>
<td>99.14%</td>
</tr>
<tr>
<td>57.74</td>
<td>0</td>
<td>99.14%</td>
</tr>
<tr>
<td>More</td>
<td>1</td>
<td>100.00%</td>
</tr>
</tbody>
</table>

Table 7-1: Velocity histogram data collected from wastewater treatment plants. Velocity bins are 5.63 cm/s wide.

Based on the results of the hydraulic experiments the following set of recommendations were developed.

I. *Rack Q should be implemented as the upstream support.* This configuration provides an increase to the turbulence intensity (12.2% increase) entering the UV rack while not significantly decreasing the residence time (4.4% decrease). In
addition, the rack Q supports are more cost effective than the present swivel supports of rack E.

II.  The maximum operating velocity of a given wastewater treatment plant will determine the size of washers to be installed.

A.  For flow velocities up to 30 cm/s, rack K (5.08 cm diameter washers) should be implemented. This rack configuration produces a 60% increase in the average turbulence intensity and an 8.2% decrease in the residence time at V = 30 cm/s, position 2.

B.  Rack P (4.76 cm diameter washers) should be used for flow velocities up to 45 cm/s. Rack P produces an average increase in turbulence intensity of 43% while decreasing the residence time by 1.5% at V = 49 cm/s, position 2.

C.  For velocities up to 52 cm/s (the maximum velocity found in Table 7-1) rack O (4.13 cm diameter) should be implemented. For rack O, an average increase in turbulence intensity of 32% was observed with a corresponding average decrease in residence time of 11% at V = 54 cm/s, position 2.
8. List of References


9. Appendices

Appendix A - Additional Data
Appendix B - Error Analysis
Appendix C - Water Surface Profiles
Appendix D - Velocity Profiles
Appendix E - Turbulence Intensity Plots
Appendix F - Standard Deviation Plots
Appendix A - Additional Data

Tables

Table A.1  Average Turbulence Intensity Data
Table A.2  Area under and maximum peaks of the RMS velocity curves for racks with washers and racks E and Q
Table A.3  Area under and maximum peaks of the RMS velocity curves for all the racks without washers
Table A.4  Plume Spreading Calculations
Table A.5  Residence Times
Table A.6  HydroQual Inc. Results of Residence Time Analysis

Figures

Figure A.1  Dye Exit Velocity vs. Dye Reservoir Height Above Water Surface
### Average Turbulence Intensity Data for racks with washers and racks E and Q

<table>
<thead>
<tr>
<th>Channel Velocity</th>
<th>E (original)</th>
<th>N (1.5&quot;)</th>
<th>O (1.625&quot;)</th>
<th>J (1.75&quot;)</th>
<th>P (1.875&quot;)</th>
<th>K (2&quot;)</th>
<th>Q (new front)</th>
<th>R (1.5&quot; &amp; 2.0&quot;)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(50 cm/s)</td>
<td>(59 cm/s max)</td>
<td>(54 cm/s max)</td>
<td>(50 cm/s max)</td>
<td>(49 cm/s max)</td>
<td>(36 cm/s max)</td>
<td>(52.8 cm/s max)</td>
<td>(41.8 cm/s max)</td>
</tr>
<tr>
<td>Vmax ====&gt;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30 cm/s at position 1</td>
<td>0.070</td>
<td>0.083</td>
<td>0.089</td>
<td>0.099</td>
<td>0.121</td>
<td>0.131</td>
<td>0.077</td>
<td>0.120</td>
</tr>
<tr>
<td>30 cm/s at position 2</td>
<td>0.066</td>
<td>0.067</td>
<td>0.073</td>
<td>0.080</td>
<td>0.094</td>
<td>0.105</td>
<td>0.074</td>
<td>0.113</td>
</tr>
<tr>
<td>Vmax at position 1</td>
<td>0.064</td>
<td>0.089</td>
<td>0.094</td>
<td>0.103</td>
<td>0.127</td>
<td>0.134</td>
<td>0.079</td>
<td>0.123</td>
</tr>
<tr>
<td>Vmax at position 2</td>
<td>0.059</td>
<td>0.069</td>
<td>0.078</td>
<td>0.082</td>
<td>0.108</td>
<td>0.107</td>
<td>0.086</td>
<td>0.119</td>
</tr>
</tbody>
</table>

### Maximum Peak of Turbulence Intensity curve

<table>
<thead>
<tr>
<th></th>
<th>E (original)</th>
<th>N (1.5&quot;)</th>
<th>O (1.625&quot;)</th>
<th>J (1.75&quot;)</th>
<th>P (1.875&quot;)</th>
<th>K (2&quot;)</th>
<th>Q (new front)</th>
<th>R (1.5&quot; &amp; 2.0&quot;)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(50 cm/s)</td>
<td>(59 cm/s max)</td>
<td>(54 cm/s max)</td>
<td>(50 cm/s max)</td>
<td>(49 cm/s max)</td>
<td>(36 cm/s max)</td>
<td>(52.8 cm/s max)</td>
<td>(41.8 cm/s max)</td>
</tr>
<tr>
<td>Vmax ====&gt;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30 cm/s at position 1</td>
<td>0.217</td>
<td>0.205</td>
<td>0.186</td>
<td>0.217</td>
<td>0.285</td>
<td>0.272</td>
<td>0.149</td>
<td>0.295</td>
</tr>
<tr>
<td>30 cm/s at position 2</td>
<td>0.151</td>
<td>0.105</td>
<td>0.101</td>
<td>0.114</td>
<td>0.189</td>
<td>0.188</td>
<td>0.163</td>
<td>0.211</td>
</tr>
<tr>
<td>Vmax at position 1</td>
<td>0.249</td>
<td>0.243</td>
<td>0.261</td>
<td>0.267</td>
<td>0.314</td>
<td>0.321</td>
<td>0.164</td>
<td>0.333</td>
</tr>
<tr>
<td>Vmax at position 2</td>
<td>0.124</td>
<td>0.115</td>
<td>0.115</td>
<td>0.132</td>
<td>0.212</td>
<td>0.193</td>
<td>0.246</td>
<td>0.231</td>
</tr>
</tbody>
</table>

Table A-1
| A-3 | 9.226 | 1.2420 | 12.690 | 1.9635 | 0.5080 | 10.4907 | 7.2976 | 6.8729 | 7.6014 | 1.9635 | 0.5080 | 10.4907 | 7.2976 | 6.8729 | 7.6014 | \( A \) | 2 | \( \delta \) | 4 | \( \alpha \) | 2 |
| 7.917 | 1.9635 | 0.5080 | 10.4907 | 7.2976 | 6.8729 | 7.6014 | 1.9635 | 0.5080 | 10.4907 | 7.2976 | 6.8729 | 7.6014 | \( A \) | 2 | \( \delta \) | 4 | \( \alpha \) | 2 |
| 5.468 | 2.1040 | 0.6227 | 1.9635 | 0.5080 | 10.4907 | 7.2976 | 6.8729 | 7.6014 | 1.9635 | 0.5080 | 10.4907 | 7.2976 | 6.8729 | 7.6014 | \( A \) | 2 | \( \delta \) | 4 | \( \alpha \) | 2 |
| 3.601 | 2.1040 | 0.6227 | 1.9635 | 0.5080 | 10.4907 | 7.2976 | 6.8729 | 7.6014 | 1.9635 | 0.5080 | 10.4907 | 7.2976 | 6.8729 | 7.6014 | \( A \) | 2 | \( \delta \) | 4 | \( \alpha \) | 2 |

**Table A.2**

**Maximum Peaks of the RMS Velocity Curves (c/s)**

**Area under the RMS Velocity Curves (1/s)**

Racks with washers and racks E and O.
Area under and maximum peaks of the RMS velocity curves for all racks without washers

### Area under RMS velocity curves for all the racks without washers (1/s)

<table>
<thead>
<tr>
<th>Velocity (cm/s)</th>
<th>Position</th>
<th>Component</th>
<th>Vmax (1/s)</th>
<th>B (50 cm/s)</th>
<th>C (50 cm/s)</th>
<th>E (original) (50 cm/s)</th>
<th>F (50 cm/s)</th>
<th>G (50 cm/s)</th>
<th>H (50 cm/s)</th>
<th>L (50 cm/s)</th>
<th>M (50 cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>1</td>
<td>x</td>
<td>398.80</td>
<td>451.60</td>
<td>361.30</td>
<td>317.20</td>
<td>378.70</td>
<td>414.90</td>
<td>456.90</td>
<td>422.40</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>1</td>
<td>y</td>
<td>499.60</td>
<td>534.70</td>
<td>366.10</td>
<td>352.40</td>
<td>419.00</td>
<td>606.50</td>
<td>571.40</td>
<td>540.30</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>1</td>
<td>z</td>
<td>334.50</td>
<td>384.90</td>
<td>332.40</td>
<td>248.40</td>
<td>346.20</td>
<td>359.70</td>
<td>383.10</td>
<td>367.60</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>2</td>
<td>x</td>
<td>415.10</td>
<td>446.80</td>
<td>320.20</td>
<td>289.70</td>
<td>333.90</td>
<td>410.20</td>
<td>448.20</td>
<td>408.00</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>2</td>
<td>y</td>
<td>551.20</td>
<td>588.20</td>
<td>352.20</td>
<td>359.60</td>
<td>384.80</td>
<td>584.20</td>
<td>604.60</td>
<td>507.90</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>2</td>
<td>z</td>
<td>342.20</td>
<td>392.40</td>
<td>315.00</td>
<td>243.80</td>
<td>317.20</td>
<td>340.20</td>
<td>377.60</td>
<td>360.50</td>
<td></td>
</tr>
</tbody>
</table>

### Maximum Peaks of the Standard Deviation curves (cm/s)

<table>
<thead>
<tr>
<th>Velocity (cm/s)</th>
<th>Position</th>
<th>Component</th>
<th>Vmax (1/s)</th>
<th>B (1/s)</th>
<th>C (1/s)</th>
<th>E (original) (1/s)</th>
<th>F (1/s)</th>
<th>G (1/s)</th>
<th>H (1/s)</th>
<th>L (1/s)</th>
<th>M (1/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>2</td>
<td>z</td>
<td>4.229</td>
<td>6.759</td>
<td>5.611</td>
<td>2.962</td>
<td>4.039</td>
<td>4.150</td>
<td>6.316</td>
<td>5.440</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Vmax (1/s)</th>
<th>Position</th>
<th>Component</th>
<th>B (1/s)</th>
<th>C (1/s)</th>
<th>E (original) (1/s)</th>
<th>F (1/s)</th>
<th>G (1/s)</th>
<th>H (1/s)</th>
<th>L (1/s)</th>
<th>M (1/s)</th>
</tr>
</thead>
</table>

Table A-3
Channel Velocity = 30 cm/s

<table>
<thead>
<tr>
<th>Position</th>
<th>Line of best fit</th>
<th>End points</th>
<th>End points</th>
<th>Position</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>base</td>
<td>top slope</td>
<td>bottom slope</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Q - new frost end</td>
<td>-0.135</td>
<td>0.058</td>
<td>0.193</td>
</tr>
<tr>
<td>1/3 downstream</td>
<td>N - 1.5&quot;</td>
<td>-0.122</td>
<td>0.088</td>
<td>0.210</td>
</tr>
<tr>
<td>middle of lights</td>
<td>J - 1.75&quot;</td>
<td>-0.117</td>
<td>0.133</td>
<td>0.249</td>
</tr>
<tr>
<td></td>
<td>K - 2&quot;</td>
<td>-0.136</td>
<td>0.148</td>
<td>0.285</td>
</tr>
<tr>
<td></td>
<td>R - 1.5&quot; &amp; 2&quot;</td>
<td>-0.116</td>
<td>0.167</td>
<td>0.283</td>
</tr>
<tr>
<td>2/3 downstream</td>
<td>Q - new frost end</td>
<td>-0.118</td>
<td>0.034</td>
<td>0.152</td>
</tr>
<tr>
<td>middle of lights</td>
<td>K - 2&quot;</td>
<td>-0.135</td>
<td>0.169</td>
<td>0.169</td>
</tr>
<tr>
<td></td>
<td>R - 1.5&quot; &amp; 2&quot;</td>
<td>-0.127</td>
<td>0.122</td>
<td>0.248</td>
</tr>
<tr>
<td>1/3 downstream</td>
<td>Q - new frost end</td>
<td>-0.135</td>
<td>0.098</td>
<td>0.233</td>
</tr>
<tr>
<td>very close to lights</td>
<td>J - 1.5&quot;</td>
<td>-0.139</td>
<td>0.187</td>
<td>0.326</td>
</tr>
<tr>
<td></td>
<td>K - 2&quot;</td>
<td>-0.176</td>
<td>0.256</td>
<td>0.432</td>
</tr>
<tr>
<td></td>
<td>R - 1.5&quot; &amp; 2&quot;</td>
<td>-0.094</td>
<td>0.318</td>
<td>0.413</td>
</tr>
<tr>
<td>2/3 downstream</td>
<td>Q - new frost end</td>
<td>-0.104</td>
<td>0.108</td>
<td>0.212</td>
</tr>
<tr>
<td>very close to lights</td>
<td>K - 2&quot;</td>
<td>-0.169</td>
<td>0.267</td>
<td>0.436</td>
</tr>
<tr>
<td></td>
<td>R - 1.5&quot; &amp; 2&quot;</td>
<td>-0.181</td>
<td>0.104</td>
<td>0.285</td>
</tr>
<tr>
<td>1/3 downstream</td>
<td>N - 1.5&quot;</td>
<td>-0.099</td>
<td>0.181</td>
<td>0.280</td>
</tr>
<tr>
<td>in the middle of two of the lights</td>
<td>R - 1.5&quot; &amp; 2&quot;</td>
<td>-0.187</td>
<td>0.183</td>
<td>0.371</td>
</tr>
<tr>
<td></td>
<td>R - 1.5&quot; &amp; 2&quot;</td>
<td>-0.199</td>
<td>0.171</td>
<td>0.370</td>
</tr>
<tr>
<td>2/3 downstream</td>
<td>N - 1.5&quot;</td>
<td>-0.101</td>
<td>0.172</td>
<td>0.273</td>
</tr>
<tr>
<td>in the middle of two of the lights</td>
<td>R - 1.5&quot; &amp; 2&quot;</td>
<td>-0.199</td>
<td>0.171</td>
<td>0.370</td>
</tr>
</tbody>
</table>

Line of Best Fit | Line through first and last points
<table>
<thead>
<tr>
<th>Total Slope:</th>
<th>Total Slope Endpoints</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/3 downstream</td>
<td>Q - new frost end</td>
</tr>
<tr>
<td>up near the top</td>
<td>N - 1.5&quot;</td>
</tr>
<tr>
<td>of the water</td>
<td>J - 1.75&quot;</td>
</tr>
<tr>
<td>just below the surface</td>
<td>R - 1.5&quot; &amp; 2&quot;</td>
</tr>
<tr>
<td>2/3 downstream</td>
<td>Q - new frost end</td>
</tr>
<tr>
<td>up near the top</td>
<td>N - 1.5&quot;</td>
</tr>
<tr>
<td>of the water</td>
<td>K - 2&quot;</td>
</tr>
<tr>
<td>just below the surface</td>
<td>R - 1.5&quot; &amp; 2&quot;</td>
</tr>
</tbody>
</table>

* From the plume diagrams it was difficult to accurately represent the plume outline as it was hidden by the top lamp. The slope is not exactly zero but very small in magnitude.
Residence Times and non-dimensionalized residence times for racks with washers and racks E and Q

**Residence time for a lamp length of 1.47 m, racks with washers and racks E and Q**

<table>
<thead>
<tr>
<th>Channel Velocity</th>
<th>E (original)</th>
<th>N (1.5&quot;)</th>
<th>O (1.625&quot;)</th>
<th>J (1.75&quot;)</th>
<th>P (1.875&quot;)</th>
<th>K (2&quot;)</th>
<th>Q (new front)</th>
<th>R (1.5&quot; &amp; 2.0&quot;)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vmax (50 cm/s)</td>
<td>(50 cm/s max)</td>
<td>(54 cm/s max)</td>
<td>(50 cm/s max)</td>
<td>(49 cm/s max)</td>
<td>(36 cm/s max)</td>
<td>(36 cm/s max)</td>
<td>(52.8 cm/s max)</td>
<td>(41.8 cm/s max)</td>
</tr>
<tr>
<td>30 cm/s at position 1</td>
<td>4.03</td>
<td>3.98</td>
<td>3.85</td>
<td>3.78</td>
<td>3.93</td>
<td>3.89</td>
<td>4.00</td>
<td>3.89</td>
</tr>
<tr>
<td>30 cm/s at position 2</td>
<td>4.01</td>
<td>3.87</td>
<td>3.72</td>
<td>3.67</td>
<td>3.69</td>
<td>3.68</td>
<td>3.96</td>
<td>3.73</td>
</tr>
<tr>
<td>Vmax at position 1</td>
<td>2.64</td>
<td>2.14</td>
<td>2.41</td>
<td>2.49</td>
<td>2.71</td>
<td>3.50</td>
<td>2.65</td>
<td>3.10</td>
</tr>
<tr>
<td>Vmax at position 2</td>
<td>2.64</td>
<td>2.08</td>
<td>2.35</td>
<td>2.43</td>
<td>2.60</td>
<td>3.29</td>
<td>2.66</td>
<td>2.99</td>
</tr>
</tbody>
</table>

**Non-dimensionalized residence times for the racks with washers and racks E and Q**

(Non-dimensionalized to rack E)

<table>
<thead>
<tr>
<th>Channel Velocity</th>
<th>E (original)</th>
<th>N (1.5&quot;)</th>
<th>O (1.625&quot;)</th>
<th>J (1.75&quot;)</th>
<th>P (1.875&quot;)</th>
<th>K (2&quot;)</th>
<th>Q (new front)</th>
<th>R (1.5&quot; &amp; 2.0&quot;)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vmax (50 cm/s)</td>
<td>(50 cm/s max)</td>
<td>(54 cm/s max)</td>
<td>(50 cm/s max)</td>
<td>(49 cm/s max)</td>
<td>(36 cm/s max)</td>
<td>(36 cm/s max)</td>
<td>(52.8 cm/s max)</td>
<td>(41.8 cm/s max)</td>
</tr>
<tr>
<td>30 cm/s at position 1</td>
<td>1.000</td>
<td>0.988</td>
<td>0.956</td>
<td>0.938</td>
<td>0.974</td>
<td>0.965</td>
<td>0.992</td>
<td>0.965</td>
</tr>
<tr>
<td>30 cm/s at position 2</td>
<td>1.000</td>
<td>0.965</td>
<td>0.927</td>
<td>0.915</td>
<td>0.920</td>
<td>0.918</td>
<td>0.986</td>
<td>0.928</td>
</tr>
<tr>
<td>Vmax at position 1</td>
<td>1.000</td>
<td>0.811</td>
<td>0.911</td>
<td>0.943</td>
<td>1.025</td>
<td>1.325</td>
<td>1.002</td>
<td>1.173</td>
</tr>
<tr>
<td>Vmax at position 2</td>
<td>1.000</td>
<td>0.786</td>
<td>0.891</td>
<td>0.919</td>
<td>0.985</td>
<td>1.246</td>
<td>1.006</td>
<td>1.134</td>
</tr>
</tbody>
</table>

Table A-5
## RESIDENCE TIME ANALYSIS FOR UV TEST UNIT CONFIGURATION

<table>
<thead>
<tr>
<th>Run</th>
<th>Flow (Lpm)</th>
<th>Flow (Lpm)</th>
<th>Velocity (fps)</th>
<th>Velocity (cm/sec)</th>
<th>Theor (T) (sec)</th>
<th>Mean (θ) (sec)</th>
<th>θ/T</th>
<th>Tp/θ</th>
<th>T50/θ</th>
<th>T/θ</th>
<th>T90/T10</th>
<th>E (cm²/sec)</th>
<th>Dispersion</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>379</td>
<td>0.196</td>
<td>5.97</td>
<td>37.8</td>
<td>40.2</td>
<td>1.06</td>
<td>0.73</td>
<td>0.82</td>
<td>0.67</td>
<td>2.62</td>
<td>94</td>
<td>0.073</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
<td>379</td>
<td>0.196</td>
<td>5.97</td>
<td>37.8</td>
<td>41.8</td>
<td>1.10</td>
<td>0.74</td>
<td>0.99</td>
<td>0.63</td>
<td>2.42</td>
<td>71</td>
<td>0.057</td>
</tr>
<tr>
<td>3</td>
<td>100</td>
<td>379</td>
<td>0.196</td>
<td>5.97</td>
<td>37.8</td>
<td>38.8</td>
<td>1.03</td>
<td>0.75</td>
<td>0.91</td>
<td>0.73</td>
<td>2.23</td>
<td>70</td>
<td>0.052</td>
</tr>
<tr>
<td>4</td>
<td>150</td>
<td>568</td>
<td>0.287</td>
<td>8.75</td>
<td>25.8</td>
<td>28.4</td>
<td>1.10</td>
<td>0.94</td>
<td>0.98</td>
<td>0.78</td>
<td>1.50</td>
<td>21</td>
<td>0.012</td>
</tr>
<tr>
<td>5</td>
<td>150</td>
<td>568</td>
<td>0.287</td>
<td>8.75</td>
<td>25.8</td>
<td>29.5</td>
<td>1.14</td>
<td>1.09</td>
<td>0.98</td>
<td>0.82</td>
<td>1.36</td>
<td>13</td>
<td>0.007</td>
</tr>
<tr>
<td>6</td>
<td>150</td>
<td>568</td>
<td>0.287</td>
<td>8.75</td>
<td>25.8</td>
<td>30.0</td>
<td>1.16</td>
<td>1.12</td>
<td>1.03</td>
<td>0.78</td>
<td>1.41</td>
<td>15</td>
<td>0.009</td>
</tr>
<tr>
<td>7</td>
<td>250</td>
<td>946</td>
<td>0.468</td>
<td>14.3</td>
<td>15.9</td>
<td>21.4</td>
<td>1.38</td>
<td>1.03</td>
<td>1.01</td>
<td>0.83</td>
<td>1.31</td>
<td>17</td>
<td>0.007</td>
</tr>
<tr>
<td>8</td>
<td>250</td>
<td>946</td>
<td>0.468</td>
<td>14.3</td>
<td>15.9</td>
<td>20.5</td>
<td>1.29</td>
<td>0.97</td>
<td>0.98</td>
<td>0.90</td>
<td>1.12</td>
<td>11</td>
<td>0.004</td>
</tr>
<tr>
<td>9</td>
<td>400</td>
<td>1514</td>
<td>0.733</td>
<td>22.3</td>
<td>10.2</td>
<td>12.6</td>
<td>1.23</td>
<td>0.95</td>
<td>0.97</td>
<td>0.90</td>
<td>1.22</td>
<td>64</td>
<td>0.016</td>
</tr>
<tr>
<td>10</td>
<td>400</td>
<td>1514</td>
<td>0.733</td>
<td>22.3</td>
<td>10.2</td>
<td>12.3</td>
<td>1.20</td>
<td>0.98</td>
<td>0.98</td>
<td>0.92</td>
<td>1.07</td>
<td>10</td>
<td>0.002</td>
</tr>
<tr>
<td>11</td>
<td>550</td>
<td>2082</td>
<td>0.997</td>
<td>30.4</td>
<td>7.5</td>
<td>9.5</td>
<td>1.26</td>
<td>0.97</td>
<td>0.98</td>
<td>0.92</td>
<td>1.14</td>
<td>9</td>
<td>0.002</td>
</tr>
<tr>
<td>12</td>
<td>550</td>
<td>2082</td>
<td>0.997</td>
<td>30.4</td>
<td>7.5</td>
<td>8.7</td>
<td>1.16</td>
<td>0.99</td>
<td>0.98</td>
<td>0.88</td>
<td>1.17</td>
<td>19</td>
<td>0.003</td>
</tr>
<tr>
<td>13</td>
<td>550</td>
<td>2082</td>
<td>0.997</td>
<td>30.4</td>
<td>7.5</td>
<td>8.0</td>
<td>1.07</td>
<td>0.99</td>
<td>0.98</td>
<td>0.84</td>
<td>1.25</td>
<td>28</td>
<td>0.004</td>
</tr>
</tbody>
</table>

Average | 1.17 | 0.94 | 0.97 | 0.81 | 1.52 | 24* | 0.019

* Geometric Mean

Table A-6
# Appendix B - Error Analysis

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>B.1</td>
<td>Estimates of Channel Velocity</td>
<td>B-2</td>
</tr>
<tr>
<td>B.2</td>
<td>Setting the Channel Flow Rate</td>
<td>B-4</td>
</tr>
<tr>
<td>B.3</td>
<td>Elbow Meter Velocity</td>
<td>B-6</td>
</tr>
<tr>
<td>B.4</td>
<td>ADV Velocity</td>
<td>B-7</td>
</tr>
<tr>
<td>B.5</td>
<td>Temperature Variations</td>
<td>B-10</td>
</tr>
<tr>
<td>B.6</td>
<td>Water Height Measurements</td>
<td>B-11</td>
</tr>
<tr>
<td>B.7</td>
<td>Dye Plume Widths</td>
<td>B-11</td>
</tr>
<tr>
<td>B.8</td>
<td>Sampling Times</td>
<td>B-12</td>
</tr>
<tr>
<td>B.9</td>
<td>Average Turbulence Intensity</td>
<td>B-13</td>
</tr>
</tbody>
</table>
B.1 Estimates of Channel Velocity

For each experiment the channel velocity was set in accordance with the velocity calculated using the upstream elbow meter. In order to check its accuracy, ADV measurements were sampled across the cross-section of the channel. Figure B-1 shows the points at which velocity measurements were sampled. Velocities were acquired upstream and downstream of Rack E as well as within the rack at four axial locations.

Figure B-1: ADV sampling positions across the cross-section of the channel. Position of the quartz sleeves are also illustrated.

One-minute velocity samples were acquired downstream of rack E at each cross-sectional location and the averaged data was inputted into an 11 by 14 cell grid (each cell has an area of 3 cm x 3 cm) modelling the cross-sectional area of the channel. Figure B-2 shows the grid along with the positions of the ADV velocity data points, A through J. Since the velocity was measured at a finite number of positions, it was possible to estimate the velocities throughout the channel cross-section by scaling these appropriately. The
missing values along the central vertical and horizontal columns, both at a distance of 15 cm from the origin in Figure B-2, were calculated by linearly interpolating between the known values (A-J); the velocities at \(\alpha\), \(\delta\) and \(\psi\), for example, were calculated in this manner. In order to compute the velocities in the other cells of the cross-section, the vertical profile was scaled according to the entries along the horizontal velocity profile. As an example, the velocity at \(\beta\) was calculated from the ratio of \(\psi\) to \(C\) and multiplied by the velocity at \(\alpha\); the velocity at \(\phi\) was computed from the ratio of \(\delta\) to \(\psi\) and then multiplied by \(\beta\). For the rest of the cross-section, the velocities were estimated in similar fashion by starting in the centre and working out towards the boundaries.

![Table B-1](image)

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
<th>J</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure B-2: Cell positions, A through J, of the ADV velocity measurements. Approximate channel dimensions (30 cm x 39 cm) are displayed along the left and bottom boundaries of the grid. Each cell has an area of 9 cm\(^2\).

Once the velocities in individual cells were calculated, they were multiplied by the area of each cell and the entire array was summed to give the total flow rate. This value was then divided by the area of the channel in order to calculate an average velocity over the entire cross-section. Table B-1 below compares the velocities as computed from the elbow meter, the above method of interpolating over the channel cross-section and the velocity of a single ADV point located midway across the channel at a height of 14.7 cm
above the channel bottom. Assuming that the interpolation method gives the correct answer, from the table it can be seen that the elbow meter overestimates the velocity by 9.2% at 30 cm/s and by 6.6% at 50 cm/s. The ADV sampled at one point also overestimates the average velocity by 17.4% and 12.0% at 30 cm/s and 50 cm/s respectively.

From the above analysis it is evident that the velocity data collected by the ADV overestimates the actual velocities present within the channel. However, the bias error introduced by the ADV will be present in all the data because each experiment was conducted in the same manner. Consequently, the velocity data associated with a particular rack will be offset by the above amounts but it is the relative differences between racks which are of importance. Since each rack configuration will have been equally affected by this offset, comparisons between the racks can still made.

<table>
<thead>
<tr>
<th>Approximate Velocity (cm/s)</th>
<th>Elbow Meter velocity (cm/s)</th>
<th>Area of channel method (cm/s)</th>
<th>ADV sampled at one point (cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>30.83</td>
<td>28.24</td>
<td>33.14</td>
</tr>
<tr>
<td>50</td>
<td>49.39</td>
<td>46.32</td>
<td>51.87</td>
</tr>
</tbody>
</table>

Table B-1: Comparison of velocities as calculated by the elbow meter, the cross-sectional area of the channel.

B.2 Setting the Channel Flow Rate

For each experiment, the channel flow rate was set by using the upstream elbow meter. As a result, it is necessary to examine the repeatability and accuracy of setting the flow rate or mean velocity using this procedure. The downstream velocity data collected with the ADV for the different racks, at positions 1 and 2, were averaged and are presented below in Table B-2. Data for racks K and racks N through R were not included.
in the 50 cm/s column as these racks were tested at their own maximum velocities. From the data it can be seen that setting the flow rate via the elbow meter produced errors in mean channel velocities ranging from ±0.71 cm/s (±2.2%) at 30 cm/s to ±0.92 cm/s (±1.8%) at 50 cm/s. The consistent ADV downstream velocities demonstrate that by using the elbow meter, the channel flow rates could be precisely controlled thereby ensuring that all the experiments were conducted at similar flow conditions.

<table>
<thead>
<tr>
<th>Rack</th>
<th>=30 cm/s</th>
<th>=50 cm/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elbow Meter</td>
<td>30.83</td>
<td>49.39</td>
</tr>
<tr>
<td>B</td>
<td>32.81</td>
<td>50.78</td>
</tr>
<tr>
<td>C</td>
<td>31.24</td>
<td>48.73</td>
</tr>
<tr>
<td>E</td>
<td>33.04</td>
<td>50.65</td>
</tr>
<tr>
<td>F</td>
<td>33.29</td>
<td>50.65</td>
</tr>
<tr>
<td>G</td>
<td>32.72</td>
<td>51.79</td>
</tr>
<tr>
<td>H</td>
<td>33.69</td>
<td>51.64</td>
</tr>
<tr>
<td>J</td>
<td>32.13</td>
<td>50.17</td>
</tr>
<tr>
<td>K</td>
<td>31.24</td>
<td>N.A.</td>
</tr>
<tr>
<td>L</td>
<td>32.09</td>
<td>50.34</td>
</tr>
<tr>
<td>M</td>
<td>32.85</td>
<td>51.35</td>
</tr>
<tr>
<td>N</td>
<td>32.00</td>
<td>N.A.</td>
</tr>
<tr>
<td>O</td>
<td>32.57</td>
<td>N.A.</td>
</tr>
<tr>
<td>P</td>
<td>31.68</td>
<td>N.A.</td>
</tr>
<tr>
<td>Q</td>
<td>32.70</td>
<td>N.A.</td>
</tr>
<tr>
<td>R</td>
<td>32.36</td>
<td>N.A.</td>
</tr>
<tr>
<td>Mean</td>
<td>32.43</td>
<td>50.68</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>±0.71 (±2.2%)</td>
<td>±0.92 (±1.8%)</td>
</tr>
</tbody>
</table>

Table B-2: Mean axial velocities measured 1 metre downstream of the racks and 14.7 cm above the channel bottom with the ADV. Overall mean and standard deviations are also included. N.A. - Racks without velocity measurements at 50 cm/s were instead run at their respective maximum velocities and therefore those values are not included in the mean or standard deviation.
B.3 Elbow Meter Velocity

Some of the errors in the elbow meter velocity can be attributed to errors in reading the manometer and in setting the downstream water surface height. The graduated scale located near the manometer is divided into increments of tenths of decimal feet and can be read to an accuracy of ±3.04 mm (±0.10 of a decimal foot) and the downstream water heights can be measured to ±1.6 mm. Since the manometer heights are related to the inlet flow rate of the channel and the downstream water surface height defines the cross-sectional area of the channel, there is an associated error in the velocity calculated by the elbow meter. The error associated in a quantity $P$, that is the product of two others, $X_1$ and $X_2$ (i.e. $P = bX_1X_2$), is given by:

$$
\sigma_P^2 = b^2 \left[ X_1^2 \sigma_{X_1}^2 + X_2^2 \sigma_{X_2}^2 \right] \quad (B-1)
$$

where $b$ is a constant without error, $\sigma_P$ is the variance in $P$ and $\sigma_{X_1}$ and $\sigma_{X_2}$ are the variances in $X_1$ and $X_2$. In this case, since $Q = VA = Vwh$, then $X_1 = V$, $X_2 = h$ and:

$$
\sigma_Q^2 = w^2 \left( V^2 \sigma_v^2 + h^2 \sigma_h^2 \right) \quad (B-2)
$$

$\sigma_Q$ is the calculated variance in the flow rate, $w$ is the width of the channel, $V$ is the channel velocity, $\sigma_h$ is the variance in the water height, $h$ is the downstream water height and $\sigma_v$ is the variance in the channel velocity [Kennedy & Neville, 1976]

Table B-3 summarizes the errors associated with each of the above quantities and the estimated error in velocities were found to be ±0.49 cm/s at a channel velocity of 30.83 cm/s and at a velocity of 49.39 cm/s the error was equal to ±0.18 cm/s. The total error actually decreases as channel velocity increases due to the fact that the errors in both
the downstream water depth and manometer reading remain constant so that the relative value decreases.

<table>
<thead>
<tr>
<th></th>
<th>Manometer reading (cm)</th>
<th>Water height (cm)</th>
<th>Area (cm²/s)</th>
<th>Q (flow rate) (cm³/s)</th>
<th>Velocity (cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30.89 cm/s</td>
<td>± 0.30</td>
<td>± 0.16</td>
<td>± 6.01</td>
<td>± 585</td>
<td>± 0.49</td>
</tr>
<tr>
<td>49.39 cm/s</td>
<td>± 0.30</td>
<td>± 0.16</td>
<td>± 6.01</td>
<td>± 361</td>
<td>± 0.18</td>
</tr>
</tbody>
</table>

Table B-3: Resulting errors in channel error, flow rate and velocity due to inaccurate manometer and downstream water height measurement.

B.4 ADV Velocity

The errors associated with the ADV velocity measurements were examined and divided into three distinct groups: the factory specified measurement error, errors associated with the ADV angle to the flow and water temperature measurement error. SonTek, the manufacturer of the ADV, quote the accuracy of the ADV at measuring mean velocities as ±0.5% or ±0.25 cm/s whichever is greater. In addition, there is an error created by the noise present within the individual samples. For velocity data acquired at 25 Hz, this error is estimated at 1% of the velocity range setting (100 cm/s). This effect will decrease with increasing sample size and was calculated as ± 0.008 cm/s and ±0.013 cm/s at channel velocities of 30 cm/s and 50 cm/s respectively [Craig Huhta, per. comm.].

During the experiments, the ADV was held in position by a modified equatorial telescope mount. The mount, shown in Figure B-3, allowed the probe to be positioned in a variety of different locations and angles of orientation. Given the mount's construction, there were six directions of motion which could be achieved but during most experiments only three were varied (A, D and F). Rotation of the probe in the direction of C and D were thought to cause the greatest error during the velocity measurements. As a result,
the movement about C was minimized by setting and locking the angle \( \theta_{cd} \) at 90° during the experiments. In order to position the ADV properly it was necessary to rotate the probe about D as it was moved axially along the length of the rack. The vertical alignment of the ADV about D was checked prior to each test with a set of three air-bubble levels that were fastened to the probe itself. This method of calibration is accurate to ±2° from the vertical. The ±2° inaccuracy in the vertical alignment translates into an error in the x-component of velocity of ±1.05 cm/s at a mean channel velocity of 30 cm/s and ±1.74 cm/s at a channel velocity of 50 cm/s. In the y-component of velocity these errors are ±0.02 cm/s and ±0.03 cm/s at channel velocities of 30 cm/s and 50 cm/s respectively. Rotations about B in Figure B-3 occurred during the experiments to determine the velocity profile across the entire cross-section. For the other experiments, the pivot at B was locked and remained fixed throughout. The error incurred due to misalignment however, is ±2° and therefore, the error in the z-component of velocity is ±1.05 cm/s at a mean channel velocity of 30 cm/s and ±1.74 cm/s at a channel velocity of 50 cm/s.
Figure B- 3: Schematic of the mount used to hold the ADV. Movement parallel to A is along the axial length of the lamps and movement along F is across the channel. The ADV is held in the collar.
B.5 Temperature Variations

As mentioned previously, the ADV measures the fluid velocity through the use of sound waves. The velocity of these sound waves however, is dependent on both the medium and the temperature of the medium through which the waves pass. Although the water used in the experiments was changed regularly, it was not tested for variations in salinity but it is assumed that these changes were negligible. The temperature of the water though did change quite dramatically depending on the time of day that experiments were conducted and on the outside weather. Water temperature was measured using an Orion digital thermometer which can measure temperatures to an accuracy of ±0.2 °C. Although the ADV requires a temperature input (this value was entered prior to each experiment) the error associated with the temperature probe must still be considered. The speed of sound in water is given by:

\[ v = \sqrt{\frac{B_m}{\rho}} \]  

(B-3)

\( B_m \) is the bulk modulus of the fluid and \( \rho \) is the density of the liquid. Since the density of water varies with temperature, the error incurred by the temperature probe will appear in the ADV velocity data. A ±0.2°C temperature difference will result in a ±0.039 kg/m³ difference in water density (CRC, 1986) and a ±2.9 cm/s difference in the speed of sound in water at 20°C. The velocity that is calculated by the ADV is taken from the following relation:

\[ v = \frac{\Delta f c_w}{2f_i} \]  

(B-4)
This equation relates the velocity of the surrounding fluid, \( v \), to the change in frequency, \( \Delta f \), experienced by sound waves reflecting off particles in the water, the speed of sound in water, \( c \), and the frequency of the original signal, \( f_0 \). Given the parameters \( f_0 = 10 \) MHz and \( \Delta f = 2020.81 \) Hz (channel velocity \(-30 \) cm/s) and \( \Delta f = 3368.01 \) Hz (channel velocity \(-50 \) cm/s) the error in the ADV measured velocity associated with the \( \pm 0.2^\circ \text{C} \) temperature difference is \( \pm 0.0006 \) cm/s at 30 cm/s and \( \pm 0.001 \) cm/s at 50 cm/s. Due to the small magnitude of these errors the effects of the temperature discrepancies can be considered negligible.

B.6 Water Height Measurements

As discussed previously, the water surface levels were measured by affixing a ruler near the water surface and videotaping the entire length of the rack. By measuring and comparing the on-screen water height to the on-screen reference distance, it is possible to calculate the actual water surface level. This scaling procedure however, introduces an error of \( \pm 1 \) mm from the reference distance and the water surface level can be measured to an accuracy of \( \pm 2 \) mm. The videotape was viewed on a 14 inch video monitor and care was taken to ensure that all measurements were obtained near the middle of the screen where the edge effects of the curved screen were minimal. Together these errors referenced to the magnified screen combine to produce an overall error of \( \pm 1 \) mm in the actual water surface level data.

B.7 Dye Plume Widths

The dye plume widths were measured directly from a computer monitor by identifying the outline of the plume. Each image is composed of a 320 by 240 pixel array
and the accuracy of locating the exact position of the plume outline with the mouse pointer was ±2 pixels. This inaccuracy was found to produce a maximum error in the slope of ±0.037.

**B.8 Sampling Times**

In order to accurately represent the velocities present within the channel, it was necessary to determine an adequate duration for the ADV sampling time. The ADV was placed upstream of the rack and a sample time of ten minutes and two of five minutes were taken. This data was partitioned into one minute samples and the means and standard deviations of each was calculated. From the analysis it was concluded that the means of the velocity could be read to an accuracy of ±2.10 cm/s, ±0.79 cm/s and ±1.53 cm/s for the x, y and z components of velocity respectively with a 90% confidence at a channel velocity of approximately 50 cm/s. The standard deviations were found to be accurate to ±1.13 cm/s for the x-component, ±0.47 cm/s for the y-component and ±0.85 cm/s for the z component also with a 90% confidence at a channel velocity of 50 cm/s. At channel velocities of 30 cm/s the mean velocities were accurate to ± 1.61 cm/s, ±0.47 cm/s and ±0.66 cm/s for the x-, y- and z-components of velocity. The standard deviations were calculated as ±0.70 cm/s for the x-component, ±0.11 cm/s for the y-component and ±0.45 cm/s for the z component. The errors quoted at a channel velocity of 30 cm/s are calculated at the 90% confidence limit. Table B-4 shows the averaged data of both the velocity and standard deviations from the ten and five minute samples. Table B-5 summarizes the mean values of the velocities and standard deviations and also shows the standard deviations of both these quantities. Also shown are the standard deviations of
the one minute means as well as the standard deviations of the one minute standard deviations. The 90% confidence limits were calculated based on the maximum standard deviations of the mean velocities and their standard deviations.

B.9 Average Turbulence Intensity

The turbulence intensity given by equation 12 is dependent on both the mean velocity and the root mean square of the fluctuating velocity. Therefore, the errors associated with these quantities will affect the calculated average turbulence intensity. The estimate of the error in the variance squared is given by:

\[
\frac{\Delta \sigma^2}{\sigma^2} = \sqrt{\left(\frac{\Delta \sigma_x}{\sigma_x^2}\right)^2 + \left(\frac{\Delta \sigma_y}{\sigma_y^2}\right)^2 + \left(\frac{\Delta \sigma_z}{\sigma_z^2}\right)^2}
\]  \hspace{1cm} (B - 4)

where the quantities \(\Delta \sigma_x, \sigma_x, \Delta \sigma_y, \sigma_y, \Delta \sigma_z,\) and \(\sigma_z\) are tabulated in Table B-5 and B-6 for channel velocities of 30 and 50 cm/s. The value of \(\sigma^2\) was calculated from the actual velocity data. The total error in \(\sigma^2\) was estimated as \(\pm 8.3\%\) for experiments conducted at a channel velocity of 30 cm/s, and \(\pm 10.8\%\) for a channel velocity of 50 cm/s. The error in mean velocity was estimated as being essentially equivalent to the error in the y-component of velocity, the main flow direction, since the magnitudes of x- and z-components were negligible in comparison. For example, for a channel velocity of approximately 30 cm/s, \(v_x=32\) cm/s, \(v_y=0.42\) cm/s, and \(v_z=1.09\) cm/s (Table B-5).

With these constituent errors, a total error in the upstream intensity, \(I_U\), was estimated as being \(\pm 12\%\) and \(\pm 13.5\%\) for channel velocities of 30 cm/s and 50 cm/s respectively. From these values, a total error in the average turbulence intensity within the rack was calculated as approximately \(\pm 2.4\%\) or \(\pm 4.0\%\) for racks with or without washers,
respectively, at 30 cm/s, and ±2.8% (with washers) or ±4.5% (without washers) at 50 cm/s. Table B-6 provides a summary of the total errors in the ADV velocity measurements.
### A 10 minute sample partitioned into 1 minute groups

#### Channel velocity of 50 cm/s

<table>
<thead>
<tr>
<th>Direction</th>
<th>Velocity (cm/s)</th>
<th>Standard Deviations (cm/s)</th>
<th>Number of samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 min</td>
<td>-0.302 48.936 2.960</td>
<td>1 min 3.838 2.758 3.430</td>
<td>150</td>
</tr>
<tr>
<td>1 min</td>
<td>-0.300 48.704 2.032</td>
<td>1 min 3.508 2.797 3.173</td>
<td>150</td>
</tr>
<tr>
<td>1 min</td>
<td>2.665 50.177 3.262</td>
<td>1 min 4.386 2.962 3.368</td>
<td>150</td>
</tr>
<tr>
<td>1 min</td>
<td>-1.474 48.841 1.074</td>
<td>1 min 2.945 2.628 2.876</td>
<td>150</td>
</tr>
<tr>
<td>1 min</td>
<td>-0.961 48.662 2.087</td>
<td>1 min 3.219 2.812 3.099</td>
<td>150</td>
</tr>
<tr>
<td>1 min</td>
<td>1.744 49.239 2.937</td>
<td>1 min 4.547 2.792 4.048</td>
<td>150</td>
</tr>
<tr>
<td>1 min</td>
<td>-0.464 49.531 2.058</td>
<td>1 min 3.386 3.583 3.924</td>
<td>150</td>
</tr>
<tr>
<td>1 min</td>
<td>0.536 49.178 3.146</td>
<td>1 min 3.641 2.571 3.179</td>
<td>150</td>
</tr>
<tr>
<td>1 min</td>
<td>-0.142 48.624 3.025</td>
<td>1 min 3.815 2.864 3.155</td>
<td>150</td>
</tr>
<tr>
<td>1 min</td>
<td>-0.847 49.911 1.654</td>
<td>1 min 3.375 2.614 2.850</td>
<td>150</td>
</tr>
<tr>
<td>10 min</td>
<td>0.045 49.080 2.424</td>
<td>10 min 3.892 2.886 3.404</td>
<td>1500</td>
</tr>
</tbody>
</table>

### 5 minute samples partitioned into 1 minute groups

#### Mean Velocities

<table>
<thead>
<tr>
<th>30 cm/s</th>
<th>Pos. 1</th>
<th>Mean Velocities</th>
<th>Standard Deviations</th>
<th>Number of samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 min</td>
<td>-0.370</td>
<td>31.991 0.761</td>
<td>x 2.172 1.715 1.729</td>
<td>150</td>
</tr>
<tr>
<td>1 min</td>
<td>-0.574</td>
<td>31.917 0.750</td>
<td>y 2.308 1.828 1.971</td>
<td>150</td>
</tr>
<tr>
<td>1 min</td>
<td>-1.185</td>
<td>31.837 0.304</td>
<td>z 2.290 1.760 2.163</td>
<td>150</td>
</tr>
<tr>
<td>1 min</td>
<td>-1.020</td>
<td>31.840 0.117</td>
<td>x 2.308 1.761 1.966</td>
<td>150</td>
</tr>
<tr>
<td>1 min</td>
<td>-0.017</td>
<td>32.179 0.863</td>
<td>y 2.239 1.819 1.913</td>
<td>150</td>
</tr>
<tr>
<td>1 min</td>
<td>-0.633</td>
<td>31.953 0.559</td>
<td>z 2.303 1.781 1.975</td>
<td>150</td>
</tr>
</tbody>
</table>

#### Standard Deviations

<table>
<thead>
<tr>
<th>30 cm/s</th>
<th>Pos. 2</th>
<th>x 3.345 1.860 2.446</th>
<th>y 1.870 2.522</th>
<th>150</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 min</td>
<td>1.582</td>
<td>32.190 1.553</td>
<td>z 2.359 1.821 1.886</td>
<td>150</td>
</tr>
<tr>
<td>1 min</td>
<td>1.378</td>
<td>32.373 1.325</td>
<td>x 2.359 1.821 1.886</td>
<td>150</td>
</tr>
<tr>
<td>1 min</td>
<td>-0.353</td>
<td>31.741 1.038</td>
<td>y 2.458 1.824 2.105</td>
<td>150</td>
</tr>
<tr>
<td>1 min</td>
<td>-0.113</td>
<td>32.047 0.491</td>
<td>z 2.365 1.708 2.026</td>
<td>150</td>
</tr>
<tr>
<td>5 min</td>
<td>0.416</td>
<td>32.012 1.086</td>
<td>x 2.837 1.835 2.239</td>
<td>7500</td>
</tr>
</tbody>
</table>

### 100 cm/s, Pos. 1

<table>
<thead>
<tr>
<th>30 cm/s</th>
<th>x 1.606</th>
<th>47.297 1.368</th>
<th>y 3.969 2.981 3.517</th>
<th>150</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 min</td>
<td>1.400</td>
<td>47.270 1.089</td>
<td>z 4.148 2.593 3.177</td>
<td>150</td>
</tr>
<tr>
<td>1 min</td>
<td>-1.134</td>
<td>46.710 0.997</td>
<td>x 3.593 2.782 3.000</td>
<td>150</td>
</tr>
<tr>
<td>1 min</td>
<td>-0.064</td>
<td>47.369 0.154</td>
<td>y 3.383 2.496 3.513</td>
<td>150</td>
</tr>
<tr>
<td>1 min</td>
<td>1.378</td>
<td>47.692 0.232</td>
<td>z 4.949 2.904 3.890</td>
<td>150</td>
</tr>
<tr>
<td>5 min</td>
<td>0.637</td>
<td>47.268 0.706</td>
<td>x 4.182 2.775 3.480</td>
<td>7500</td>
</tr>
</tbody>
</table>

### 50 cm/s, Pos. 2

<table>
<thead>
<tr>
<th>50 cm/s</th>
<th>x -0.139</th>
<th>47.063 0.313</th>
<th>y 4.111 2.862 3.373</th>
<th>150</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 min</td>
<td>-1.563</td>
<td>46.957 0.483</td>
<td>z 3.466 2.864 3.054</td>
<td>150</td>
</tr>
<tr>
<td>1 min</td>
<td>-0.900</td>
<td>47.082 0.147</td>
<td>x 3.206 2.639 2.968</td>
<td>150</td>
</tr>
<tr>
<td>1 min</td>
<td>-1.784</td>
<td>46.922 1.937</td>
<td>y 4.975 3.168 4.003</td>
<td>150</td>
</tr>
<tr>
<td>1 min</td>
<td>-0.731</td>
<td>47.300 0.231</td>
<td>z 4.162 2.755 4.059</td>
<td>150</td>
</tr>
<tr>
<td>5 min</td>
<td>-1.023</td>
<td>47.065 0.370</td>
<td>x 4.074 2.865 3.611</td>
<td>7500</td>
</tr>
</tbody>
</table>

**Table B-4**
<table>
<thead>
<tr>
<th>Time</th>
<th>Standard Deviation of the means</th>
<th>90% Confidence</th>
<th>90% Confidence</th>
<th>90% Confidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 min</td>
<td>0.06 0.06</td>
<td>0.07 0.07</td>
<td>0.09 0.09</td>
<td>0.11 0.11</td>
</tr>
<tr>
<td>10 min</td>
<td>0.14 0.14</td>
<td>0.16 0.16</td>
<td>0.18 0.18</td>
<td>0.20 0.20</td>
</tr>
</tbody>
</table>

Mean Values of the velocities

Channel Velocity 30 cm/s

Channel Velocity 50 cm/s

5 and 10 Minute Velocity Data Samples
## Errors in ADV Velocity Measurement

### Channel Velocity = 30 cm/s

<table>
<thead>
<tr>
<th>Error Name</th>
<th>x</th>
<th>y</th>
<th>z</th>
<th>x</th>
<th>y</th>
<th>z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Factory Specifications</td>
<td>0.14</td>
<td>0.14</td>
<td>0.14</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Holding the ADV vertical</td>
<td>1.05</td>
<td>0.02</td>
<td>1.05</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Temperature reading</td>
<td>0.0004</td>
<td>0.0004</td>
<td>0.0004</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>10 and 5 minute data samples (max. error from Table B-5)</td>
<td>0.98</td>
<td>0.29</td>
<td>0.40</td>
<td>0.42</td>
<td>0.06</td>
<td>0.28</td>
</tr>
</tbody>
</table>

**Sum of errors**

| 2.17 | 0.45 | 1.59 | 0.43 | 0.07 | 0.29 |

**90 % confidence**

| 3.58 | 0.75 | 2.62 | 0.70 | 0.11 | 0.47 |

### Channel Velocity = 50 cm/s

<table>
<thead>
<tr>
<th>Error Name</th>
<th>x</th>
<th>y</th>
<th>z</th>
<th>x</th>
<th>y</th>
<th>z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Factory Specifications</td>
<td>0.14</td>
<td>0.14</td>
<td>0.14</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Holding the ADV vertical</td>
<td>1.74</td>
<td>0.03</td>
<td>1.74</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Temperature reading</td>
<td>0.0006</td>
<td>0.0006</td>
<td>0.0006</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>10 and 5 minute data samples (max. error from Table B-5)</td>
<td>1.27</td>
<td>0.48</td>
<td>0.93</td>
<td>0.69</td>
<td>0.29</td>
<td>0.52</td>
</tr>
</tbody>
</table>

**Sum of errors**

| 3.15 | 0.65 | 2.81 | 0.70 | 0.30 | 0.53 |

**90 % confidence**

| 5.19 | 1.08 | 4.63 | 1.15 | 0.49 | 0.87 |

Note: The last row under the standard deviation gives the error in sigma (delta sigma).

Table B-6
Appendix C - Water Surface Profiles

Water surface profiles for each rack at a channel velocity of 30 cm/s and maximum operational velocities. Water surface elevation of -1 cm corresponds to the top of the uppermost lamps.
Appendix D - Velocity Profiles

Velocity versus \( y \) measured at transverse positions 1 and 2 for all racks at channel velocities of 30 cm/s and maximum operational velocities.
Channel Velocity 30 cm/s position 2

- Channel Velocity: 30 cm/s
- Position: 2
- Rack E

Graphs showing:
- Channel Velocity (x vel.)
- Y-axis velocity (y vel.)
- Z-axis velocity (z vel.)

Axis:
- X-axis: y (cm)
- Y-axis: x vel. (cm/s)
- Y-axis: y vel. (cm/s)
- Y-axis: z vel. (cm/s)

Graphs illustrate velocity changes with respect to position along the y-axis.
Channel Velocity 50 cm/s position 2

Rack E

x vel. (cm/s)

y (cm)

-50  0  50  100  150  200  250

-2  0  1  2

y vel. (cm/s)

y (cm)

-50  0  50  100  150  200  250

45  50  55  60  65

z vel. (cm/s)

y (cm)

-50  0  50  100  150  200  250

-1  0  0.5  1
<table>
<thead>
<tr>
<th>Channel</th>
<th>Velocity 30 cm/s position 1</th>
<th>Rack N</th>
</tr>
</thead>
<tbody>
<tr>
<td>x vel. (cm/s)</td>
<td><img src="image1" alt="Graph" /></td>
<td></td>
</tr>
<tr>
<td>y vel. (cm/s)</td>
<td><img src="image2" alt="Graph" /></td>
<td></td>
</tr>
<tr>
<td>z vel. (cm/s)</td>
<td><img src="image3" alt="Graph" /></td>
<td></td>
</tr>
</tbody>
</table>
Channel Velocity 59 cm/s position 1
Rack N

$\text{Channel Velocity } 59 \text{ cm/s position } 1 \quad \text{Rack N}$
Channel Velocity 59 cm/s position 2  Rack N

Graphs showing:
- **X velocity (cm/s)**
- **Y velocity (cm/s)**
- **Z velocity (cm/s)**

Axes:
- X velocity (cm/s) vs. y (cm)
- Y velocity (cm/s) vs. y (cm)
- Z velocity (cm/s) vs. y (cm)
Channel Velocity 30 cm/s position 1  Rack O

- x vel. (cm/s)
- y vel. (cm/s)
- z vel. (cm/s)
Channel Velocity 30 cm/s position 2  

Rack O

Graphs showing velocity along x, y, and z axes with respect to position along the y-axis (cm).
Channel Velocity 54 cm/s position 1

Rack O

x vel. (cm/s)

y (cm)

y vel. (cm/s)

y (cm)

z vel. (cm/s)

y (cm)
Channel Velocity 30 cm/s position 1  

Rack J

Graphs showing velocity measurements:

1. X velocity (cm/s) vs y (cm)
2. Y velocity (cm/s) vs y (cm)
3. Z velocity (cm/s) vs y (cm)
Channel Velocity 30 cm/s position 2 Rack J
Channel Velocity 30 cm/s position 1 Rack P
Channel Velocity 49 cm/s position 2

Rack P

- x vel. (cm/s)
- y vel. (cm/s)
- z vel. (cm/s)
Channel Velocity 30 cm/s position 2

Rack K

- Graph 1: x vel. (cm/s)
- Graph 2: y vel. (cm/s)
- Graph 3: z vel. (cm/s)
Channel Velocity 36 cm/s position 1
Rack K

- x vel. (cm/s)
- y vel. (cm/s)
- z vel. (cm/s)
Channel Velocity 36 cm/s position 2

Rack K
Channel Velocity 30 cm/s position 1

x vel. (cm/s)

y (cm)

y (cm)

z vel. (cm/s)

y (cm)
Channel Velocity 30 cm/s position 2

Rack Q

x vel. (cm/s)

y vel. (cm/s)

z vel. (cm/s)
Channel Velocity 52 cm/s position 1
Rack Q

x vel. (cm/s)

y (cm)

y vel. (cm/s)

y (cm)

z vel. (cm/s)

y (cm)
Channel Velocity 52 cm/s position 2

- Channel Velocity vs. Position
- X Velocity vs. Y Position
- Y Velocity vs. Y Position
- Z Velocity vs. Y Position

Rack Q
Channel Velocity 30 cm/s position 2  
Rack R

- x vel. (cm/s)
- y vel. (cm/s)
- z vel. (cm/s)
Channel Velocity 41 cm/s position 1

- x vel. (cm/s)
- y vel. (cm/s)
- z vel. (cm/s)

Rack R
Channel Velocity 30 cm/s position 2

- x velocity (cm/s)
- y velocity (cm/s)
- z velocity (cm/s)

Rack C

y (cm)

y (cm)

y (cm)
Channel Velocity 50 cm/s position 1

Rack C

x vel. (cm/s)

y (cm)

y vel. (cm/s)

z vel. (cm/s)

y (cm)
Channel Velocity 50 cm/s position 2

Rack C

x vel. (cm/s)

y (cm)

y vel. (cm/s)

y (cm)

z vel. (cm/s)

y (cm)
Channel Velocity 30 cm/s position 1

Rack F

- x vel. (cm/s)
- y vel. (cm/s)
- z vel. (cm/s)

y (cm)

-50 0 50 100 150 200 250

-2 0 1 2

-50 0 50 100 150 200 250

-2 0 1 2
Channel Velocity 30 cm/s position 2

Rack F

- Y (cm)
- x vel. (cm/s)

- y (cm)
- y vel. (cm/s)

- z vel. (cm/s)
Channel Velocity 50 cm/s position 2

Rack F

- x vel. (cm/s)
- y vel. (cm/s)
- z vel. (cm/s)

y (cm)
Channel Velocity 30 cm/s position 1

- x vel. (cm/s)

- y vel. (cm/s)

- z vel. (cm/s)
Channel Velocity 30 cm/s position 2

Rack G

x vel. (cm/s)

y (cm)

y vel. (cm/s)

y (cm)

z vel. (cm/s)

y (cm)
Channel Velocity 50 cm/s position 1

- x vel. (cm/s)
- y vel. (cm/s)
- z vel. (cm/s)
Channel Velocity 30 cm/s position 2

Rack H

x vel. (cm/s)

y vel. (cm/s)

z vel. (cm/s)
Channel Velocity 50 cm/s position 1

Rack H

$\text{y (cm)}$

$\text{x vel. (cm/s)}$

$\text{y vel. (cm/s)}$

$\text{z vel. (cm/s)}$
Channel Velocity 30 cm/s position 2

Rack L

x vel. (cm/s)

y (cm)

y vel. (cm/s)

y (cm)

z vel. (cm/s)

y (cm)
Channel Velocity 30 cm/s position 1

Rack M

Graph showing x-velocity, y-velocity, and z-velocity over a range of y (cm) values from -50 to 250 cm.
Channel Velocity 30 cm/s position 2

Rack M

x vel.(cm/s)

y (cm)

y vel.(cm/s)

y (cm)

z vel.(cm/s)

y (cm)
Channel Velocity 50 cm/s position 1

Rack M

x vel. (cm/s)

y (cm)

-50 0 50 100 150 200 250

-6 -4 -2 0 2 4 6

y vel. (cm/s)

y (cm)

-50 0 50 100 150 200 250

45 50 55 60

z vel. (cm/s)

y (cm)

-50 0 50 100 150 200 250

-2 -1 0 1 2
Channel Velocity 50 cm/s position 2

Rack M

x vel. (cm/s)

y (cm)

y vel. (cm/s)

y (cm)

z vel. (cm/s)

y (cm)
Appendix E - Turbulence Intensity Plots

Turbulence intensity as a function of axial distance $y$ for the racks with washers and for racks E and Q. Measurements were conducted at a channel velocity of 30 cm/s and at maximum operational velocities at transverse positions 1 and 2.
Turbulence intensity at 30 cm/s position 1 Rack E

Turbulence intensity at 30 cm/s position 2 Rack E
Turbulence Intensity at 30 cm/s position 1  Rack N

Turbulence Intensity at 30 cm/s position 2  Rack N
Turbulence Intensity at 30 cm/s position 1  Rack O

Turbulence Intensity at 30 cm/s position 2  Rack O
Turbulence intensity at 50 cm/s position 1

Turbulence intensity at 50 cm/s position 2
Turbulence intensity at 30 cm/s position 1  Rack P

Turbulence intensity at 30 cm/s position 2  Rack P
Turbulence Intensity at 49 cm/s position 1  Rack P

Turbulence Intensity at 49 cm/s position 2  Rack P
Turbulence intensity at 36 cm/s position 1
Rack K

Turbulence intensity at 36 cm/s position 2
Rack K
Turbulence intensity at 30 cm/s position 1 Rack R

Turbulence intensity at 30 cm/s position 2 Rack R
Appendix F - Standard Deviation Plots

RMS velocities as a function of axial distance $y$ for all the racks. Measurements were conducted at a channel velocity of 30 cm/s and at maximum operational velocities at transverse positions 1 and 2.
Standard deviations at a channel velocity of 30 cm/s. Position 1. Rack E
Standard deviations at a channel velocity of 30 cm/s. Position 2. Rack E
Standard deviations at a channel velocity of 50 cm/s. Position 1. Rack E

1. Sigma x (cm/s)
2. Sigma y (cm/s)
3. Sigma z (cm/s)
Standard deviations at a channel velocity of 50 cm/s. Position 2. Rack E
Standard deviations at a channel velocity of 30 cm/s. Position 1  Rack N
Standard deviations at a channel velocity of 30 cm/s. Position 2  Rack N
Standard deviations at a channel velocity of 59 cm/s. Position 1  Rack N
Standard deviations at a channel velocity of 59 cm/s. Position 2 Rack N

- **σ** (cm/s)
- y (cm)
Standard deviations at a channel velocity of 30 cm/s. Position 1  Rack O
Standard deviations at a channel velocity of 30 cm/s. Position 2  Rack O

- $\sigma_{\text{max}}$ (cm/s)
- $\sigma_{\text{m}}$ (cm/s)
- $\sigma_{\text{z}}$ (cm/s)

$y$ (cm)
Standard deviations at a channel velocity of 54 cm/s. Position 1 Rack 0
Standard deviations at a channel velocity of 54 cm/s. Position 2   Rack O
Standard deviations at a channel velocity of 30 cm/s. Position 1  Rack J

- $\sigma_{max}$ (cm/s)
- $\sigma_y$ (cm/s)
- $\sigma_z$ (cm/s)
Standard deviations at a channel velocity of 30 cm/s. Position 2  Rack J
Standard deviations at a channel velocity of 50 cm/s. Position 1  Rack J
Standard deviations at a channel velocity of 50 cm/s. Position 2 Rack J
Standard deviations at a channel velocity of 30 cm/s. Position 1  Rack P
Standard deviations at a channel velocity of 30 cm/s. Position 2 Rack P
Standard deviations at a channel velocity of 49 cm/s. Position 1 Rack P
Standard deviations at a channel velocity of 49 cm/s. Position 2  Rack P
Standard deviations at a channel velocity of 30 cm/s. Position 1 Rack K
Standard deviations at a channel velocity of 30 cm/s. Position 2  Rack K
Standard deviations at a channel velocity of 36 cm/s. Position 1 Rack K
Standard deviations at a channel velocity of 36 cm/s. Position 2 Rack K
Standard deviations at a channel velocity of 30 cm/s. Position 1  Rack Q
Standard deviations at a channel velocity of 30 cm/s. Position 2  Rack Q
Standard deviations at a channel velocity of 52 cm/s. Position 1  Rack Q
Standard deviations at a channel velocity of 52 cm/s. Position 2 Rack Q
Standard deviations at a channel velocity of 30 cm/s. Position 1  Rack R
Standard deviations at a channel velocity of 30 cm/s. Position 2 Rack R
Standard deviations at a channel velocity of 41 cm/s. Position 1 Rack R

- $\sigma_x$ (cm/s)
- $\sigma_y$ (cm/s)
- $\sigma_z$ (cm/s)

Graphs showing the standard deviations for $\sigma_x$, $\sigma_y$, and $\sigma_z$ as a function of $y$ (cm) for Position 1 Rack R.
Standard deviations at a channel velocity of 41 cm/s. Position 2  Rack R
Standard deviations at a channel velocity of 30 cm/s. Position 1. Rack C
Standard deviations at a channel velocity of 30 cm/s. Position 2. Rack C

- **sigma x (cm/s)**
- **sigma y (cm/s)**
- **sigma z (cm/s)**
Standard deviations at a channel velocity of 50 cm/s. Position 1. Rack C
Standard deviations at a channel velocity of 50 cm/s. Position 2. Rack C
Standard deviations at a channel velocity of 30 cm/s. Position 1. Rack F
Standard deviations at a channel velocity of 30 cm/s. Position 2, Rack F.
Standard deviations at a channel velocity of 50 cm/s. Position 1. Rack F.
Standard deviations at a channel velocity of 50 cm/s. Position 2. Rack F
Standard deviations at a channel velocity of 30 cm/s. Position 1. Rack G
Standard deviations at a channel velocity of 30 cm/s. Position 2. Rack G
Standard deviations at a channel velocity of 50 cm/s. Position 1. Rack G
Standard deviations at a channel velocity of 50 cm/s. Position 2. Rack G
Standard deviations at a channel velocity of 30 cm/s. Position 1. Rack H
Standard deviations at a channel velocity of 30 cm/s. Position 2. Rack H
Standard deviations at a channel velocity of 50 cm/s. Position 1. Rack H
Standard deviations at a channel velocity of 50 cm/s. Position 2. Rack H
Standard deviations at a channel velocity of 30 cm/s. Position 1. Rack L
Standard deviations at a channel velocity of 30 cm/s. Position 2. Rack L
Standard deviations at a channel velocity of 50 cm/s. Position 1. Rack L
Standard deviations at a channel velocity of 50 cm/s. Position 2. Rack L
Standard deviations at a channel velocity of 30 cm/s. Position 1. Rack M
Standard deviations at a channel velocity of 30 cm/s. Position 2. Rack M
Standard deviations at a channel velocity of 50 cm/s. Position 1. Rack M
Standard deviations at a channel velocity of 50 cm/s. Position 2. Rack M