Project #: E-20-X77
Center #: 10/24-6-R7927-0A0
Contract#: AWD DATED 930907
Subprojects ?: N
Main project #:

Project unit: CIVIL ENGR
Project director(s):
AMIRTHARAJAH A

Sponsor/division names: MARIETTA WATER AUTH - COBB
Sponsor/division codes: 300 / 019

Award period: 930701 to 950630 (performance) 950630 (reports)

Sponsor amount
Contract value 54,011.00
Funded 54,011.00

Cost sharing amount 0.00

Does subcontracting plan apply ?: N
Title: STATIC MIXERS FOR COAGULATION

PROJECT ADMINISTRATION DATA

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Security class (U,C,S,TS) : U
Defense priority rating : N/A
Equipment title vests with: Sponsor
NONE PROPOSED OR ANTICIPATED
Administrative comments -
INITIATION OF PROJECT E-20-X77.
GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

NOTICE OF PROJECT CLOSEOUT

Closeout Notice Date 09/01/95

Project No. E-20-X77          Center No. 10/24-6-R7927-0A0
Project Director AMIRTHARAJAH A  School/Lab CIVIL ENGR
Sponsor MARIETTA WATER AUTH - COBB/
Contract/Grant No. AWD DATED 930907  Contract Entity GTRC
Prime Contract No. 
Title STATIC MIXERS FOR COAGULATION
Effective Completion Date 950630 (Performance) 950630 (Reports)

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Comments

Subproject Under Main Project No.
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NOTE: Final Patent Questionnaire sent to PDPI.
RESEARCH REPORT

EFFECTIVENESS OF STATIC MIXERS FOR COAGULATION IN WATER TREATMENT

by

B. F. Schulgen
and
A. Amirtharajah

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submitted to

The General Manager
Cobb County-Marietta Water authority

August 1995
FOREWORD AND ACKNOWLEDGEMENTS

This research report was prepared by the senior author Bradford F. Schulgen as a Master of Science Thesis and presented to the Faculty of the School of Civil and Environmental Engineering in partial fulfillment of the requirements for the degree of Master of Science. The research was supervised by Dr. Appiah Amirtharajah and the thesis has been reviewed and approved by Dr. Christine Tiller and Dr. Edward S. K. Chian of the School of Civil and Environmental Engineering. This research was completed with support provided by the Cobb County-Marietta Water Authority under Grant No. E-20-X77.

Additional research on static mixers is being conducted by S. Casey Jones as a part of his Ph.D. dissertation. A paper based on a plant scale comparison of rapid mix units at the Quarles Water Treatment Plant will be presented at the 1995 Water Quality Technology Conference to be held November 12-16, 1995 in New Orleans, Louisiana. The title of the paper and authors are as follows:

"Comparison of Plant-Scale Rapid Mix Units Using Plant Operating Date"
by
S. Casey Jones, A. Amirtharajah and P. R. Karr

These research efforts were also a part of the above project.

The authors would like to thank Dr. Philip Karr, General Manager of the Cobb County-Marietta Water Authority for his unending support throughout the duration of the study.
EFFECTIVENESS OF STATIC MIXERS FOR COAGULATION IN WATER TREATMENT

A Thesis
Presented to
The Academic Faculty

by

Bradford Forrest Schulgen

In Partial Fulfillment
of the Requirements for the Degree
Master of Science in Environmental Engineering

Georgia Institute of Technology
June, 1995
EFFECTIVENESS OF STATIC MIXERS FOR COAGULATION IN WATER TREATMENT

APPROVED:

Appiah Amirtharajah, Chairman

Christine Tiller

Edward S.K. Chian

Date Approved by Chairman May 24, 1995
DEDICATION

To my wife...

Without her support I may never have finished
ACKNOWLEDGEMENTS

I would like to express my appreciation to Dr. Appiah Amirtharajah. His knowledge and support throughout my graduate studies was invaluable. None of this would have been possible without his guidance. I would like to thank the Cobb County-Marietta Water Authority for their financial support during my graduate work. I also appreciate the time spent by Dr. Christine Tiller and Dr. Edward Chian in reviewing this paper.

I would like to thank S. Casey Jones whose ideas and critiques were always helpful, especially during difficulties in my research as well as my writing. He always seemed to have the right suggestion at the right time. Special thanks also goes to Ray Thompson of Jordan, Jones and Goulding, Inc., who volunteered to proof read this document, although I don't think he knew what he was getting into. Thanks also to Ray for being so patient and letting me get this thesis finished. Also, I would like to recognize Anne Studstill, who believed in me enough to think I could do this in the first place and helped me get through it all.

Finally, I would like to thank my family. If I did not have them I am not sure I would have ever reached this point.
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LIST OF SYMBOLS

a Empirical constant
B Empirical constant
C Empirical constant
C_6 Empirical constant
C_7 Empirical constant
C_f Flow coefficient based on Reynolds number
C_V Variation coefficient
\bar{C} Average concentration
c_i Concentration at point i
D Diameter
D_h Hydraulic diameter
D_{MAX} Maximum stable drop size
D_{32} Sauter mean diameter
d_1 Particle diameter
E_D Direct energy dissipation due to gradients of the mean velocity
f Fanning friction factor
f_D Darcy friction factor
G Velocity gradient (G-value)
GT \quad G\text{-value} \times \text{detention time}

H_f \quad \text{Headloss due to friction in the pipe}

K \quad \text{Proportionality constant dependent on the viscosity of the emulsion}

L \quad \text{Length}

L_{\text{SM}} \quad \text{Length of the static mixer}

L_{\text{EL}} \quad \text{Length of an individual mixing element}

m \quad \text{Empirical constant}

Ne \quad \text{Newton number}

n \quad \text{Number of samples}

P \quad \text{Power input}

\Delta P \quad \text{Pressure drop}

Q \quad \text{Volumetric flow rate}

Re \quad \text{Reynolds number}

S \quad \text{Standard deviation of several repeated measurements of a component}

T \quad \text{Detention time}

u \quad \text{Superficial velocity}

V \quad \text{Volume}

Vi \quad \text{Viscosity group}

We \quad \text{Weber number}
**Greek Letters**

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<tr>
<td>$\gamma$</td>
<td>Specific weight</td>
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<tr>
<td>$\epsilon$</td>
<td>Energy dissipation rate per unit mass</td>
</tr>
<tr>
<td>$\eta$</td>
<td>Kolmogoroff micro scale</td>
</tr>
<tr>
<td>$\lambda_{SM}$</td>
<td>Drag coefficient</td>
</tr>
<tr>
<td>$\nu$</td>
<td>Kinematic viscosity</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Density of the fluid</td>
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<tr>
<td>$\rho_d$</td>
<td>Density of the dispersed phase</td>
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<tr>
<td>$\mu$</td>
<td>Dynamic viscosity</td>
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<td>$\mu_d$</td>
<td>Dynamic viscosity of the dispersed phase</td>
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<td>$\Pi_C$</td>
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<td>$\xi$</td>
<td>Interfacial tension</td>
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<tr>
<td>$\sigma/\sigma_0$</td>
<td>Relative standard deviation</td>
</tr>
<tr>
<td>$\sigma_c$</td>
<td>Standard deviation of the concentration gradient</td>
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<tr>
<td>$\sigma_0$</td>
<td>Initial standard deviation</td>
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<tr>
<td>$\Sigma$</td>
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<td>$\psi$</td>
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SUMMARY

Rapid mixing is a critical part of the water treatment process. Few argue this fact, but many have different opinions on the best way to accomplish this task. Several different types of mixers are available but which is best for what application can sometimes be a difficult decision. Little research has been done in relation to the use of static mixers in the water treatment industry and in comparing the static mixer to other types of mixing processes. Because of this, design engineers have no set design parameters which can be used when selecting a static mixer for water treatment. Also unknown is the general effectiveness of static mixers for coagulation in water treatment under a variety of chemical and operational conditions. This paper will partially resolve this problem by providing some justifiable design parameters to be used for static mixers.

First, an extensive review of the literature for coagulation theory in water treatment was conducted. Next, a review of the literature relating mixing and its effects on coagulation was executed. Finally, a search for background information on the use of static mixers in other fields of application was conducted. The information from this search was related, whenever possible, to the use of static mixers in water treatment. These three subjects were selected because of their relevance to the application of static mixers in the rapid mixing process.
Five sets of experiments were conducted at various chemical conditions and over a variety of mixing intensities. Coagulant dosages ranged from 5 - 20 mg/L and pH values ranged from 6.2 - 7.4. Pressure losses across the static mixer for each set of experiments were varied from approximately 0.5 - 8.5 feet. Also, a survey was made of water treatment plants currently employing a static mixer in the rapid mixing process. Using these two information sources, comparisons were made and conclusions were reached as to the performance criteria for a static mixer. Some comparisons between the traditional backmix configuration and the static mixer were also made, as well as comparisons between the static mixer and an empty pipe.

It was found that static mixers are very effective in water treatment under several different chemical conditions. The static mixer was found to be most effective at the optimum coagulant dosages coupled with the correct pH values (i.e. proper chemical conditions). The mixer was found to be effective in both the charge neutralization as well as the sweep coagulation regimes. The mixer was also found to work well at all mixing intensities within the range of these experiments. The static mixer performed well when compared to the backmix configuration, giving almost identical results. Also, the static mixer performed better than an empty pipe in terms of settled water quality. The plant data also revealed a wide range of chemical and physical parameters over which the static mixer can be effectively operated. In general, the plant data and the experimental data provided two sources of information to be used when drawing conclusions about the design parameters of static mixers in water treatment.
CHAPTER I

INTRODUCTION

Rapid mixing is one of the key processes in water treatment. When chemicals are added to the raw water flow stream, they must be effectively mixed to be fully utilized in the treatment process. If there are deficiencies in the mixing process, excessive amounts of chemicals will have to be used to make up for the deficiency. Many different methods of effective mixing have been used including: backmix mechanical type mixers, in-line mechanical mixers, hydraulic baffled type mixers, and jet injection mixers. All of these mixers have advantages and disadvantages.

Recently, the static or motionless mixer, which is a newer type of mixer, was introduced into the water treatment industry. The static mixer has been utilized for many years in the chemical process industry to mix highly viscous, laminar flows such as polymer melts. Only recently have the turbulent flow applications of static mixers been realized. The static mixer is especially attractive for certain water treatment applications because of its fast, even distribution of mixing energy. Another attractive aspect of the static mixer is its relatively low power consumption and maintenance requirements as compared to other types of mixers. These aspects make it a more cost effective type of rapid mixer.

The static mixer basically consists of a number of baffles or mixing elements mounted in a pipe. A pump upstream of the static mixer supplies the energy for pushing the water
through the mixer. Mixing intensity within the static mixer is adjusted by changing the flow rate. While the water flows through the mixer, turbulent energy is dissipated in the water. This also happens in an empty pipe flow but at a much slower rate. The static mixer merely speeds up the energy dissipation process. Various shapes, sizes and configurations of the mixing elements have been tried, but it is still unclear which are best for water treatment applications. There is even much confusion on how much energy should be dissipated as well as how fast this should occur for effective water treatment.

The purpose of this study is to provide the design engineer some general guidelines and parameters to use when specifying a static mixer for a rapid mixing water treatment process. Very little research has been done in the water treatment field relating to static mixers and no reliable design method has been formulated. Most designs currently in place have used either manufacturer suggested values or have used "rules of thumb". As a result of this study, a more justifiable basis for selecting various design parameters of the static mixer has been developed. This was accomplished by three methods. The first method was to conduct a series of laboratory experiments over a range of mixing intensities as well as chemical conditions. The second method was to collect some "real world" data, to evaluate the current conditions under which static mixers are being used. Finally, a comparison between the experimental and "real world" data was made to help reinforce any conclusions drawn about static mixers and their design.
CHAPTER II

LITERATURE REVIEW

This chapter provides a review of current theories and literature applicable to coagulation and mixing in water treatment. Also reviewed is the available literature on static mixers, and a link is formed between the mixing capabilities of static mixers and their use in water treatment for coagulation. The main purpose of this chapter is to provide a background of knowledge which can then be used to evaluate the experimental results obtained in the research conducted. The material within is relevant, because the function of the static mixer is to provide adequate mixing of the chemicals used for coagulation in water treatment.

Coagulation

It has long been understood that an effective coagulation process is a prerequisite to effective drinking water treatment. Using a definition stated by Amirtharajah and O'Melia (1990), "Coagulation is considered to encompass all reactions, mechanisms, and results in the overall process of particle aggregation within a water being treated ..." The fundamentals of coagulation have been under much scrutiny for many years, because it has been widely thought that better ways of carrying out this step in water treatment could be developed. In general, coagulation is a physicochemical process which involves chemically treating particles
and other contaminants suspended in water to facilitate the collisions between, and aggregation of, these particles leading to their eventual removal.

The conventional surface water treatment train consists of rapid mixing, flocculation, sedimentation, and filtration. Another popular treatment scheme known as direct filtration has been employed when treating low, relatively constant turbidity source waters. This scheme eliminates the settling process, and the water flows directly from flocculation to filtration. A less widely used treatment scheme is in-line filtration, which involves using only the rapid mixing and filtration processes. In all of these treatment schemes, proper coagulation of the water has a great effect on the final water quality.

The mixing processes considered in coagulation include both the rapid mix and slow mix or flocculation processes. The key to improved coagulation seems to be in the rapid mix process, where there is a direct influence on the dispersion of chemicals used to treat the raw water. By enhancing chemical dispersion, the particles within the water are more uniformly treated. As many studies have been completed, it becomes more apparent that good mixing leads to good flocculation and then to improved settling and/or filtration. Some raw water quality parameters which affect coagulation are: turbidity, total organic carbon (TOC), color, pH, ionic strength, zeta potential, and temperature.

**Particle Stability**

Most naturally occurring particles carry a negative surface charge and are considered stable in this naturally occurring state. The goal of the coagulation process is to neutralize this negative surface charge so that collisions can occur between particles, and eventually an agglomeration of particles will be created in the flocculation process. When the particle is
sufficiently treated so that this charge has been overcome, the particle is destabilized. The net negative surface charge carried by a particle is mainly due to either solution and surface chemistry or imperfections in the structure of the particle itself. One model suggests that the negatively charged particle is surrounded by a rigid layer of positive counter ions known as the Stern layer. This in turn is surrounded by a diffuse layer of positively and negatively charged ions. The charge on the particle itself, along with all of the counter ions surrounding it, are collectively known as the electrical double layer. The zeta potential of a particle is the potential at the plane of shear within the electrical double layer. The zeta potential is dependent on the potential at the surface of the particle and the thickness of the double layer (Amirtharajah and O'Melia, 1990). Its value indicates the strength of the repulsive forces between particles. A schematic of a charged particle is shown in Figure 2.1. All of these variously charged ions result in a net electrical charge of zero in the suspension. However, the particles are prevented from agglomerating by the repulsive forces that result when the electrical double layers of two particles overlap (Amirtharajah and O'Melia, 1990).

Naturally occurring attractive forces between particles also exist. These attractive forces are known as van der Waals forces. Van der Waals forces are short range forces, so the strength of the van der Waals forces decreases with increasing distance between two particles. Thus, unless the repulsive forces between particles are reduced sufficiently to allow the particles to closely approach one another, the van der Waals forces will never be strong enough to take effect. By reducing the repulsive forces using the mechanisms of coagulation, the van der Waals forces take effect and when the particles are brought together they form aggregates.
Figure 2.1. Charged Particle in a Colloidal Suspension

(Amirtharajah and O'Melia, 1990)
Mechanisms of Coagulation

**Double layer compression.** This mechanism of coagulation occurs when there are high ion concentrations in solution with the particles. The particles are destabilized by ions carrying charges opposite to those of the particles. These ions are attracted to the charge of the particle and are present in the solution surrounding the particle. If there is a sufficient concentration of the ions in the solution, then a smaller diffuse layer surrounding the particle is required to maintain the electroneutrality of the solution. When this diffuse layer becomes small enough, the double layer is compressed and the attractive van der Waals forces which are always present between particles take over, and the particles are drawn together. This mechanism, however, does not typically apply to water treatment because of the low ionic strengths of most naturally occurring fresh waters.

**Adsorption and Charge Neutralization.** This mechanism primarily involves coagulant-colloid interactions at the particle-water interface. The charged species of the coagulant in solution is adsorbed onto the surface of the colloid. When enough charged species have been adsorbed, the natural surface charge of the particle is neutralized, and the attractive van der Waals forces dominate particle interactions. It is possible to overdose the water being treated with the coagulant, resulting in a reversal of the particle surface charge and restabilization of the particle. Usually it is ideal to produce a net charge of zero when using this mechanism of coagulation. Charge neutralization conditions can normally be obtained using a minimum dosage of coagulant. Typically this mechanism is applied to lower turbidity waters but can be used in conventional treatment or direct filtration.
**Sweep Coagulation.** When the concentration of a metal salt coagulant such as aluminum sulfate or ferric chloride is sufficiently high in a solution, a metal hydroxide precipitate is formed. The colloids in solution can become enmeshed within these precipitates as they are formed and also collide with them after they are formed (Amirtharajah and O'Melia, 1990). Once enmeshed within or attached to these precipitates, the particles will settle out with the aggregates of precipitated metal salts, or flocs, that have built up during the flocculation process. Generally, higher doses of coagulant are required to achieve sweep coagulation conditions. Sometimes additional particles must also be added to enhance the flocculation kinetics of the system under these conditions. Typically, the charge neutralization and sweep coagulation mechanisms predominate in water treatment processes.

**Adsorption and Interparticle Bridging.** Coagulation involving synthetic cationic, nonionic, and anionic polymers occurs by adsorption and interparticle bridging. The polymers act as interparticle bridges which link several particles together to form a settleable floc. A segment of a single polymer chain adsorbs onto the particle surface while the rest of the polymer chain remains free in the solution. When another segment of the same chain comes into contact with another particle, it can also adsorb onto the surface of that particle. In this way, the particles are linked together by interparticle bridges. If too much polymer is added, as with other mechanisms, the particles may become restabilized with little possibility of floc formation. This mechanism is not as common in the water treatment industry because polymers are difficult to handle and are usually much more expensive than metal salts.
Aluminum Sulfate as a Coagulant

Inorganic metal salts and high molecular weight organic polymers are the types of coagulants currently used in the water treatment industry. Simple salts do not readily work as coagulants because of their inability to promote the formation of strong aggregates. Metal salts adsorb onto the surface of the particle and form a more permanent attachment which is resistant to the shearing effects of flocculation. The most commonly used coagulant in the water treatment industry in the United States is aluminum sulfate, $\text{Al}_2(\text{SO}_4)_{18} \cdot 14.3 \text{H}_2\text{O}$ (alum). Other coagulants such as iron salts and polymers are not considered in this section because the experiments for this study were conducted using only alum as a coagulant.

Hydrolysis Speciation of Alum. Several generic reactions for the hydrolysis of alum were given by Amirtharajah and Mills (1982) based on past work done by others and are shown below.

$$\text{Al}^{3+} + \text{H}_2\text{O} \rightleftharpoons \text{AlOH}^{2+} + \text{H}^+$$

$$\text{AlOH}^{2+} + \text{H}_2\text{O} \rightleftharpoons \text{Al(OH)}_2^+ + \text{H}^+$$

$$\text{Al(OH)}_2^+ + \text{H}_2\text{O} \rightleftharpoons \text{Al(OH)}_3 + \text{H}^+$$

$$\text{Al(OH)}_3 + \text{H}_2\text{O} \rightleftharpoons \text{Al(OH)}_4^- + \text{H}^+$$

$$\text{Al(OH)}_4^- + \text{H}_2\text{O} \rightleftharpoons \text{Al(OH)}_5^{2-} + \text{H}^+$$

$$\text{Al(OH)}_5^{2-} + \text{H}_2\text{O} \rightleftharpoons \text{Al(OH)}_6^{3-} + \text{H}^+$$

From these basic species, it is possible to build more complex polymers such as $\text{Al}_{13}$(OH)$_{34}^{2+}$, $\text{Al}_8$(OH)$_{17}^{4+}$, $\text{Al}_8$(OH)$_{20}^{4+}$, and $\text{Al}_6$(OH)$_{12}^{3+}$. Although all these species are thought to be present in a given solution of alum, certain ones dominate at a given pH. It is important to determine which species are present because the various mechanisms of
coagulation are controlled by the hydrolysis speciation. When operating under the charge neutralization mechanism, the more desirable species of alum are the positively charged ions. The sweep coagulation mechanism, however, works best when the dominant form of alum species present is the solid precipitate Al(OH)₃(s). Figure 2.2 is a good illustration of sweep and charge neutralization coagulation by alum.

**Alum Coagulation Diagram.** Coagulation diagrams for metal salts have been developed to be used as guides to define operational regions most suited for the various coagulation mechanisms. An alum coagulation diagram was developed by Amirtharajah and Mills (1982) based on work done previously by several independent research teams. This diagram, presented in Figure 2.3, shows the conditions of pH and coagulant concentration that are most appropriate for the sweep and charge neutralization mechanisms. The construction of the diagram is based on the thermodynamic solubility diagram for the various alum species present in solution. Superimposed on the solubility diagram are the chemical conditions under which coagulation occurs with the different mechanisms.

There are several important constraints that must be considered when using the alum coagulation diagram (Amirtharajah and O'Melia, 1990). One such constraint is that the restabilization zone is a function of colloid surface area. The restabilization zone shown on the diagram in Figure 2.3 is based on a source water with a low colloid concentration. Higher colloid concentrations could significantly alter the zone of restabilization. Another constraint is that high concentrations of anions may suppress charge reversal and restabilization. A third constraint is based on the presence of significant concentrations of humic substances which
Figure 2.2. Illustration of Sweep and Charge Neutralization Coagulation by Alum (Amirtharajah and Mills, 1982)
Figure 2.3. Design and Operation Diagram for Alum Coagulation (Amirtharajah and Mills, 1982)
could impact the dosages of alum required and alter the coagulation zones shown on the diagram.

Effects of Rapid Mixing on Coagulation

In the past two decades, it has come to light that it is possible to design the rapid mixing process such that it may be tailored to the specific mechanism of coagulation being used. As the first step in the water treatment process, it is obvious that the rapid mixing process will have a direct bearing on the outcome of subsequent processes, and ultimately, the finished water quality. It is commonly thought that good rapid mixing will lead to better water treatment, but what defines good and poor rapid mixing is still a mystery. As stated by Amirtharajah and Mills (1982), "The major consideration in rapid mixing has been over uniform dispersion of the coagulant with the raw water in order to avoid over- and undertreatment of the water."

Rapid Mixing and Sweep Coagulation

In sweep coagulation, the aluminum hydroxide precipitate, Al(OH)$_3$ (s), is the primary species responsible for colloid removal. Research by Letterman et al. (1973) indicated that the formation of the aluminum hydroxide precipitate occurred in the time interval of 1 - 7 seconds after coagulant addition. Considering this, it is not surprising that Amirtharajah and Mills (1982) found that various intensities of rapid mixing had little effect on settled water quality as seen in Figure 2.4. Their experiments found that it was more important to have the proper chemical conditions present in rapid mixing, to facilitate the rapid precipitation of Al(OH)$_3$ (s). It was also concluded that, while the transport aspects of the rapid mix process
Figure 2.4. Effect of Rapid Mixing Intensities on Settled Water Quality for Sweep Coagulation (Amirtharajah and Mills, 1982)

were relatively unimportant for sweep coagulation, the transport aspects of the flocculation process were important. Clark et al. (1994) compared five different types of rapid mixers in the sweep coagulation regime: two backmix reactors, two in-line mixers, and an empty pipe. They found that all five mixers performed similarly for a variety of coagulant dosages and mixing intensities. Taking all of these ideas into consideration, it can be hypothesized that the best type of rapid mixing for the sweep coagulation mechanism is the backmix reactor configuration, which provides rapid mixing as well as high intensity flocculation. A backmix reactor is a tank in which a mechanically stirred impeller is used to do the mixing. Typically the backmix reactor has a detention time of less than 30 seconds. Also, some earlier design criteria suggested mixing times of one to two minutes for this reactor. The reactions for
coagulation occur much more rapidly than these time intervals which is why it is thought that some high intensity flocculation may also be occurring in this reactor configuration.

**Rapid Mixing and Charge Neutralization**

The reactions which form the hydrolyzed alum species without the alum polymers are very rapid, on the order of $10^{-4}$ seconds, and the alum hydrolysis polymers can be formed within 1 second (O'Melia, 1972; Hahn and Stumm, 1968). Because of these rapid reactions, it is necessary to mix and uniformly disperse the coagulant almost instantaneously as it is added to the process flow stream. Using this knowledge, it can be deduced that the best type of mixing for the charge neutralization mechanism would be an in-line, instantaneous mixer which produces high intensity turbulence. Several types of these mixers are available for use in the water treatment industry including: in-line blenders, radial turbine flash mixers, pump or jet injection mixers, hydraulic jump mixers, and static mixers.

Several studies seem to contradict each other on the question of whether or not the in-line mixers are really better or even necessary for adequate coagulation in the charge neutralization regime. Vrale and Jorden (1971) demonstrated that several in-line mixers performed better than a backmix reactor for charge neutralization. Kawamura (1973), however, found that there was little difference in settled water turbidity with or without the in-line mixing impeller he used in his experiments. Amirtharajah and Mills (1982) showed that the higher G-values that can be generated by in-line mixers were generally more effective when operating in the adsorption-destabilization (charge neutralization) regime as seen in Figure 2.5. Clark and Srivastava (1993) studied alum precipitation in relation to mixing and determined that higher intensities of mixing were more favorable to alum precipitation.
because the proper chemical conditions for precipitation were brought about faster. Their conclusions, however, were based primarily on measuring how quickly the pH of the solution changed during a titration and thus brought about a given desired set of chemical conditions, rather than an actual water quality study in the charge neutralization regime. They also stated that slower mixing was more favorable if polymeric species were desired because the right chemical conditions for polymeric formation were in place for a longer period of time. Klute and Dierschke’s research, presented by Klute and Amirtharajah (1990), found results which support the idea of charge neutralization coagulation requiring fast, intense mixing and dispersion for best results. Their findings support the ideas put forth by Amirtharajah and

![Figure 2.5. Effectiveness of Higher Rapid Mixing Intensities on Settled Water Quality for Charge Neutralization Coagulation (Amirtharajah and Mills, 1982)](image-url)
Mills in 1982. With so many conflicting reports on high intensity mixing and its effects on coagulation in the charge neutralization regime, it is clear that more research needs to be done in this area.

**Particle Destabilization by Inorganic Coagulants in Turbulent Fields**

The theory summarized in this section was presented by Amirtharajah and Trusler (1986) in hopes of developing a way to predict optimum rapid mixing G-values based on particle size and turbulence eddies. The G-value is a measure of the power or energy input per unit volume of a given reactor. As fluid flows through a pipe under turbulent conditions, the turbulence generated takes the form of eddies. The largest of these eddies is approximately the same size as the pipe which contains it, and most of the kinetic energy of the main flow is contained in these eddies. Inertial forces transfer energy from the largest eddies to the smallest eddies through an energy cascade. The energy is finally dissipated by the smallest eddies in the form of heat. An illustration of these turbulent eddies can be seen in Figure 2.6.

Turbulence theory considers two subranges for these smallest eddies: the viscous subrange and the inertial subrange. The viscous subrange contains the smallest of the small eddies and the inertial subrange contains larger eddy sizes. The two subranges are divided by the Kolmogoroff microscale, $\eta$, which can be calculated from the following equation:

$$\eta = \left( \frac{v^3}{\epsilon} \right)^{\frac{1}{4}}$$  \hspace{1cm} (2.1)

where $\epsilon$ is the energy input per unit mass and $v$ is the kinematic viscosity.
Amirtharajah and Trusler (1986) used accepted models of particle collisions in 
turbulent fields and the general framework for flocculation set up by O'Melia (1978, 1980) 
to develop equations predicting optimum particle destabilization. A few novel assumptions 
were made to apply the theory to rapid mixing. First, it was assumed that the hydrolyzed 
alum species were carried by turbulent eddies the size of the Kolmogorov microscale and 
interacted with the particles in the raw water when the particles collided with the eddies. 
Second, it was assumed that the number of eddies and particles remained constant throughout 
the destabilization step. Third, it was assumed that the power input into the system controls 
the size of the eddies which cause destabilization.

The final result reached by Amirtharajah and Trusler (1986) predicted that minimum 
destabilization would occur at \( \eta/d_i = 2.0 \) for the viscous subrange and at \( \eta/d_i = 1.33 \) for the 
inertial subrange, where \( d_i \) is the particle diameter. Figure 2.7 shows a schematic diagram of
destabilization due to coagulant carried in microscale eddies. When compared to their experimental results with \( d_i = 3 \, \mu m \), the theory worked fairly well but was not incontrovertible. The theory predicted that G-values of 1500 - 3500 sec\(^{-1}\) should be avoided for effective destabilization. This result also agreed with current G-values used in practice which are 700 - 1000 sec\(^{-1}\) and 3000 - 5000 sec\(^{-1}\). Amirtharajah and Trusler (1986) recommended that more experimental work be done in this area to further test the theory.

**Particle Destabilization in Turbulent Pipe Flow**

The most common form of mixing in the water treatment industry today is the traditional backmix reactor. The backmix reactor consists of a chamber through which the process water continuously flows, while the water is mixed with a mechanically operated stirrer. Recently, it has been discovered that this type of rapid mix reactor is inefficient in achieving particle destabilization by the charge neutralization mechanism (Klute and Amirtharajah, 1991). Because the reactions for destabilization using charge neutralization are very fast and essentially irreversible, a high intensity of turbulence is critical for the first few seconds after coagulant addition. The backmix reactor cannot achieve a complete and homogenous dispersion of the chemicals being added within the necessary time frame for charge neutralization reactions. Due to the inadequacy of backmix reactors, designers have gone towards designing in-line type mixers for plants operating under the charge neutralization mechanism. These types of mixers are better at evenly dispersing the chemicals over the short time frames required, while keeping energy requirements at acceptable levels.

**Calculation of Mixing Intensities.** The mixing in turbulent pipe flow is primarily caused by frictional headloss across a given length of pipe. The headloss can be converted
Figure 2.7. Schematic of Destabilization Due to Coagulants Carried in Microscale Eddies

(Amirtharajah and Trusler, 1986)

into power input by using the equation:

\[ P = Q \gamma H_f \]  

(2.2)

where \( Q \) is the flow rate, \( \gamma \) is the specific weight of the fluid, and \( H_f \) is the headloss due to friction in the pipe. Once the power input is obtained, the energy input per unit mass, \( \epsilon \), can be calculated by dividing the power input, \( P \), by the mass of fluid contained within the length of pipe across which the headloss was measured. Also, the traditional G-value can be calculated by using the equation:
where V is the volume of water into which the power is dissipated and \( \mu \) is the dynamic viscosity. The GT value is another parameter commonly used for design and is based on the required G-value and the detention time, \( T \), within the mixer. It can be calculated by multiplying the given G-value by the average detention time within the mixer.

These calculations work reasonably well when dealing with a simple empty pipe turbulent flow, but they must be questioned when applied to other types of in-line mixers such as the static mixer, the in-line blender, and the jet injection mixer. The questions arise because it is unknown exactly what volume should be considered as the mixing volume in the in-line mixers. Another problem with using the G-value as a design parameter in turbulent pipe flow is that the G-value was originally developed based on a backmix type of configuration and is essentially an average measure of several different mixing intensity zones within the backmix reactor tank (Amirtharajah and O'Melia, 1990) as illustrated in Figure 2.8. When considering pipe flow turbulence, the mixing intensity tends to be much more uniformly distributed across the cross sectional area of the pipe excluding the boundary layers, and thus an average value tends to be realistic in the fluid field when compared with a backmix reactor.

**Measuring Mixing Performance.** Klute and Amirtharajah (1991) suggest two different ways of measuring mixer performance in a pipe. The first involves the calculation of a variation coefficient, \( C_v \), which is used as a measure of the uniformity of mixing of a
ZONE OF MAXIMUM TURBULENCE
\[ P_m1 \approx 50\bar{P}_m \]
\[ V_1 \approx 0.005V \]
\[ G_1 \approx 7\bar{G} \]

IMPELLER STREAM ZONE
\[ P_m2 \approx 5.4\bar{P}_m \]
\[ V_2 \approx 0.095V \]
\[ G_2 \approx 2.3\bar{G} \]

BULK ZONE
\[ P_m3 \approx 0.25\bar{P}_m \]
\[ V_3 \approx 0.9V \]
\[ G_3 \approx 0.5\bar{G} \]

TOTAL VOLUME = \( V = V_1 + V_2 + V_3 \)
AVERAGE POWER DISSIPATION PER UNIT VOLUME = \( \bar{P} \)
AVERAGE VELOCITY GRADIENT = \( \bar{G} \)

Figure 2.8. Partitioned Energy Dissipation in a Stirred Vessel

(Amirtharajah and O'Melia, 1990)

given tracer substance in the main pipe flow. The variation coefficient is calculated from the formula:

\[ C_v = \frac{\sigma_c}{\bar{C}} \] (2.4)

where \( \sigma_c \), the standard deviation of the concentration gradient, can be calculated from the following equation:

\[ \sigma_c = \sqrt{\frac{\sum_{i=1}^{n} (c_i - \bar{C})^2/(n-1)}{n-1}} \] (2.5)

where \( c_i \) is the concentration at point \( i \) within the cross sectional area and \( \bar{C} \) is the average concentration of the chemical used for destabilization.
Tracer substances which can be used as measurement tools include acids, bases, salts, and dyes. Conductivity, pH, and light adsorption measurements are used to characterize and analyze the concentration of these tracers.

The second measurement tool for evaluating mixing efficiency is to measure the electrophoretic mobility or zeta potential of samples taken along the length of the mixer, downstream of the chemical injection point. This gives a direct measurement of the particle destabilization occurring in the mixer. Sample points should be located along the length of the mixer as well over the cross sectional area of the mixer, to get a clear understanding of what is happening inside the mixer. It may also be useful to calculate the mean value, the distribution, and the standard deviation of the electrophoretic mobility to statistically evaluate the thoroughness of the mixing.

**Static Mixers**

Static mixers are a relatively new technology developed extensively for the chemical process industry over the past thirty years. Personnel in the water treatment industry have recently acquired an interest in the performance of static mixers for applications such as rapid mixing because of the short residence time and high intensity mixing inherent in the static mixer. Pahl and Muschelknautz (1982) estimated that there are about 30 different types of static mixers known today with applications in both the laminar and turbulent flow regimes. Mutsakis and Rader (1986) state that about a dozen of these designs are useful to the water and wastewater treatment industries. However, a very limited amount of research has been done directly related to mixing in the water treatment industry.
A static mixer mainly consists of stationary elements placed end to end within a pipe. Several different element geometries for static mixers may be seen in Figure 2.9. The elements are designed so that they divide, recombine, and redirect the fluid flowing through them. By doing this, the elements cause an increased turbulent energy dissipation rate above the rate that is normally present in turbulent pipe flow. This turbulence is what provides the energy for the mixing of chemicals with the process flow. The degree of homogeneity or mixing quality in the process flow increases exponentially with each additional element

Figure 2.9. Various Element Geometries for Several Different Types of Static Mixers:
   a) Ross-ISG Mixer, b) Pulsating Mixing Reactor, c) PSM Mixer, d) Kenics Mixer,
   e) Erestat Mixer, f) N-Shaped Pipe Mixer, g) SMV Mixer, h) SMX Mixer, i) In-Line-Blender,
The optimum design is to find a minimum number of elements to produce the desired amount of mixing. Many different geometries have been developed by various mixing companies and several are described very well by Pahl and Muschelknautz (1982). Because a static mixer operates as an in-line mixer, it can be considered a plug flow reactor with very little backmixing.

Static mixers were originally developed with the mixing of highly viscous fluids in mind. Consequentially, most of the research has been done in the laminar flow regime, which is usually more applicable when dealing with high viscosity fluids. However, as Godfrey and Amirtharajah (1991) state, "it soon became apparent that there were turbulent-flow applications for the static mixer." Godfrey (1985) makes the point that even though static mixers were originally developed with the laminar flow range in mind, there are probably more applications in turbulent flow now. In a simple empty pipe at high flow rates, a sufficient amount of mixing based on the large scale turbulence of the flow occurs, but concentration gradients can be observed at distances of 40 to 50 pipe diameters downstream (Klute and Amirtharajah, 1991). A static mixer is more efficient and generates fast, intense radial mixing, reducing the required pipe length for complete homogenization of the process flow to a fraction of that for the empty pipe.

Advantages and Disadvantages of the Static Mixer

Static mixers primarily compete with the traditional backmix or stirred tank reactor for use in the process and water treatment industries. They have a number of advantages and disadvantages when compared to the backmix configuration. An important advantage is that the static mixer creates a much more uniform turbulence throughout the mixing volume as
opposed to a stirred tank agitator, which has high intensity turbulence only in an immediate zone around the impeller. A second advantage is that the static mixer typically requires a much smaller volume to do the same amount of mixing as a backmix reactor, and therefore, it takes up less space. Considering energy consumption, the static mixer requires very little power to operate. Also, there are a wide variety of materials that may be utilized to build the static mixer, and, provided there is a sufficient length of pipe, it can be retrofitted in a variety of installations. Static mixers require very little maintenance and only periodic cleaning of the mixing elements is necessary to prevent excessive build up of dirt, chemicals, etc. Finally, the static mixer gives a predictable and repeatable mixing performance under a given set of conditions (Godfrey, 1985).

A disadvantage of the static mixer is that there is no easy way to adjust mixing intensity. This is significant because the mixing intensity varies as the flow changes and cannot be held constant, unlike the backmix reactor which can be adjusted with changes in the flow. If the flow varies too much, then the mixing intensity may become too low or too high. This can result in poor treatment in the case of low flow. In the case of high flow, the static mixer may require more headloss than the plant has available, thus limiting the maximum amount of water which can be treated by the plant. These limits are important constraints and should be carefully evaluated whenever the installation of a static mixer is being considered. Another limitation which is not very obvious is that there is almost no axial mixing in the static mixer, and consequentially, the feed stream and process flow must be held at a relatively constant ratio (Godfrey, 1985). This must be done to avoid over or under treatment of the water. Stirred tanks, however, provide a buffer against small flow
fluctuations. One possible solution to this problem would be to install an in-line monitoring device which could automatically adjust for changes in the flow or raw water quality. Other small disadvantages are the possibility of blockage occurring in the mixing elements, the difficulty of removing and installing additional elements, and the lack of visual observation of the treatment process.

Cost Benefits

Several authors have performed a cost comparison between static mixers and mechanically stirred type reactors. In general, it is obvious that even if a static mixer has a slightly higher initial cost than the mechanical mixer, it will be less expensive over a period of several years because of reduced operation and maintenance costs. Mechanical mixers require significant amounts of power if they are to be constantly running. They also require constant maintenance and parts replacement. Static mixers only require a small amount of additional pumping energy and periodic cleaning. McDonough (1992) actually reports a lower capital cost for static mixers as compared to mechanically stirred, as well as lower operations costs. McKenna et al. (1986) performed a present worth cost analysis over a twenty year period comparing a static mixer to a mechanical stirrer. They found that, although the static mixer cost more initially, the mechanical stirrer cost almost twice as much as the static mixer for the given twenty year interval when power consumption was considered. Clark et al. (1994) shows that for a larger water treatment plant (>100 mgd) the static mixer has a lower initial capital cost than the backmix reactor, but it is more expensive than the hydraulic jet mixer. It does not appear that Clark et al. (1994) considered the
additional and significant operation and maintenance costs associated with the use of the mechanically stirred agitator.

Another operational cost benefit of static mixers in water treatment is a reduction in treatment chemical costs. By blending the treatment chemicals more effectively, smaller amounts of chemicals are required to get the same finished water quality. Mutsakis and Rader (1986) report lower chemical consumption figures at several installations in the water and wastewater treatment field, although no actual data are given. McKenna et al. (1986) found a 30 percent reduction in chlorine dosage for a given level of fecal coliform kill required in their wastewater treatment configuration. Schutz (1988) discovered a significantly improved yield (15 - 30 percent higher) of a desired product when comparing rapid exothermic reactions carried out in a static mixer as opposed to a mechanically agitated thin-film reactor. Clark et al. (1994) reported an optimum coagulant dose for static mixers 35 to 40 percent less than the dose required for backmix reactors and stated that "it appears that the two in-line initial mixers (static and hydraulic jet) can achieve performance equivalent to the backmixing-type mixers at a lower coagulant dose." Overall, it seems that static mixers are a more cost effective type of mixing operation due to their efficient, rapid dispersion of chemicals and low operation and maintenance costs.

Static Mixers and Laminar Flow

Laminar flow mixing is not a primary concern in the water treatment industry because most flows in water treatment are highly turbulent. Mixing in laminar flow usually occurs due to the "random rearrangement of fluid regions in an uncontrolled flow process" (Godfrey, 1985) and is typically associated with fluids of high viscosity. Static mixers help enhance this
rearrangement process by splitting and redirecting the flow paths to recombine with one another at set intervals downstream. This creates a controlled and more efficient rearrangement of the fluids to be mixed. Meyer et al. (1988) performed micromixing experiments comparing a static mixer to an empty pipe operating in the laminar flow range and found significant improvement of the mixing quality for both slower and faster chemical reactions when a static mixer was used.

In the design of static mixers for laminar flow, the ratio of total length of mixing elements to nominal pipe diameter, $L_{SM}/D$ is often used as a guide to selecting the number of elements needed to achieve a specific mixture quality. Another mixture quality parameter frequently used is the variation coefficient presented in equation 2.4 (Godfrey, 1985; Godfrey and Amirtharajah, 1991; Mutsakis and Rader, 1986), where the well mixed condition is represented by $C_v = 0.05$. Finally, pressure loss across the static mixer must be considered when designing the mixer. Usually this parameter is supplied by the manufacturer for a given number of elements at a given flow rate and may be defined by the ratio $\Delta P/\Delta P_o$, which is the ratio of the pressure loss across the static mixer to that across an equivalent length of empty pipe.

**Static Mixers and Turbulent Flow**

The application of static mixers to mixing in turbulent pipe flow is what most interests water treatment engineers. The fast, uniform radial dispersion of chemicals into the process flow by the static mixer seems ideally suited for the charge neutralization mechanism of coagulation where the chemical reactions taking place typically occur in less than one second. The static mixer allows the level of turbulence in a pipe to be raised without changing the pipe
diameter or the flow rate through the pipe. Energy utilization is also better in a static mixer in the turbulent flow regime because the energy is dissipated more equally throughout the volume of the mixer, as opposed to the unequal energy dispersion in a backmix reactor.

**Pressure Drop Across the Static Mixer.** One of the first things considered when evaluating a static mixer for use in a water treatment plant is the headloss or pressure drop across the static mixer. The pressure drop can be considered a measure of the turbulent energy input into the mixing system. A significant amount of headloss across the static mixer is inherent to its function of creating more turbulence than an empty pipe flow and it cannot be avoided. It can, however, be minimized by proper design of the mixing element geometry and by the selection of the optimum pipe size and number of mixing elements. Kawamura (1991) suggests a maximum of 2 feet of headloss across the static mixer. Monk and Trussell (1991) recommend designing the static mixer based on the GT value required and selecting the most appropriate model from the manufacturer's data.

Several methods for determining headloss across the mixer are suggested in the literature and will be reviewed here. The simplest way is to take several measurements at various flow rates using a differential pressure measuring device and create a calibration curve for the specific static mixer being used. This technique is not always easily performed, however, especially by the engineer in the design phase of a project, who has no working model. The designer must get headloss information from the manufacturer. Bourne and Maire (1991) suggested using the dimensionless Newton number, Ne, to obtain headloss from the equation:

$$\Delta P = N_e p \frac{u^2}{L/D}$$

(2.6)
where $\Delta P$ is the pressure drop, $\rho$ is the density of the fluid, $u$ is the superficial velocity of the fluid in the pipe, $L$ is the length of the mixer, and $D$ is the pipe diameter. Kabatek et al. (1989) suggested the equation:

$$\Delta P = \lambda_{SM} \rho \left( \frac{u^2}{2} \right) \left( \frac{L}{D} \right)$$  \hspace{1cm} (2.7)

where $\lambda_{SM}$ is a drag coefficient and is a function of Reynolds number, $Re$, using the empirical relation as follows:

$$\lambda_{SM} = B + \frac{C}{Re}$$  \hspace{1cm} (2.8)

where $B$ and $C$ are constants and

$$Re = \frac{Du\rho}{\mu}.$$  \hspace{1cm} (2.9)

Pahl and Muschelknautz (1982) put forth an equation very similar to equation 2.7, the only real difference being their use of the symbol $\phi_D$ in the place of $\lambda_{SM}$. They also state that $\phi_D$ is a function of Reynolds number and mixer element geometry. It can be seen that all of these methods have a common basis and simply utilize different dimensionless numbers to describe the frictional or drag aspects of the static mixer. Other authors (Godfrey, 1985; McDonough, 1992) provide pressure loss relationships which have been developed for a specific manufacturer's static mixing element and should only be used for that type of element.

**Effects of the Number of Mixing Elements.** Because of the additional turbulence and radial mixing generated, the homogeneity of the system will increase with each mixing element added to the static mixer. There is, however, an associated increase in the pressure
drop with the addition of each element. It can be concluded that there is some optimum number of elements which balances acceptable pressure losses with required homogeneity of the system. For fast chemical reactions, Bourne and Maire (1991) found that five elements provided adequate mixing of the chemical processes they studied. Clark et al. (1994) reported little difference between using two or five mixing elements in the sweep coagulation regime for water treatment. Taweel and Walker (1983) determined that the most efficient energy utilization by a static mixer occurred with four elements, the total range of their experiments covering 4 - 36 elements. It is possible that the number of mixing elements should only be considered as a function of other parameters such as headloss, required homogeneity, and detention time within the mixer.

**Length to Diameter Ratios.** Several authors in the literature discuss design of the static mixer in terms of length to diameter ratio, L/D. This parameter can be considered in terms of both the length of individual elements and the length of a series of elements. Godfrey and Amirtharajah (1991) reported that Sulzer (a static mixer manufacturer) recommends that individual element lengths should be equal to one pipe diameter for pipe sizes less than 100 mm (4 in) and that for pipe diameters greater than 100 mm the element length should be one-half the pipe diameter. Kabatek et al. (1989) presented information on a new type of static mixer known as Helax with the length of one element being 1.3 D and gave additional information on the length of a Kenics static mixer being 1.5 - 2.0 D. Although there are many other types of static mixers available, it is probably safe to say that most will have individual element lengths in the range of 0.5 - 2.0 D.
The other use of the L/D term is in reference to the total length of several mixing elements used in a static mixer. L/D in this context is directly related to the number of elements as discussed previously. To avoid further confusion of this matter, \( L_{EL} \) will be used to represent the length of one element, and \( L_{SM} \) will be used to represent the total length of mixing elements within the static mixer. With this considered, several authors report good mixing within an \( L_{SM}/D \) range of approximately 3 - 9 (Pahl and Muschelknautz, 1982; Taweel and Walker, 1983; Godfrey and Amirtharajah, 1991; Bourne and Maire, 1991).

**Detention Time Within the Static Mixer.** Detention time, \( T \), is defined as the average amount of time that a single particle or element of fluid spends within a given mixing vessel. Given that a static mixer operates as a plug flow reactor, the detention time can be calculated by dividing the volume, \( V \), of the length of pipe containing the static mixing elements by the volumetric flow rate, \( Q \), flowing through the pipe, or \( T = V/Q \). For a true detention time, the volume displaced by the static mixing elements themselves should be subtracted from the total pipe volume and this number should be used as \( V \).

When considering fast chemical reactions such as those occurring during charge neutralization coagulation, the detention time becomes an important factor. As stated previously in the section entitled "Effects of Rapid Mixing on Coagulation," the chemical reactions needed for the charge neutralization mechanism occur in the time range of \( 10^4 \) - 1 second. With this in mind, the static mixer should be designed to disperse most of its turbulent energy within one second of coagulant addition to make the most effective use of the turbulent energy. It should also be kept in mind that as the flow rate varies, the detention time will change, as well as the turbulent energy dissipated by the static mixer. Kawamura
(1991) recommends a detention time of 1 - 3 seconds for most water treatment applications using static mixers.

**Introduction of the Fluid to be Dispersed.** The point at which the treatment chemicals are injected into the flow stream is an important parameter in pipeline mixing. If the chemicals are injected at the proper point in the pipeline, then the effectiveness of the static mixer can be increased and fewer elements will be needed to adequately mix the process flow. Most authors recommend that the feed stream be injected at the center of the pipeline carrying the static mixer (Pahl and Muschelknautz, 1982; Berkman and Calabrese, 1988; Kabatek et al., 1989; Bourne and Maire, 1991; Klute and Amirtharajah, 1991; McDonough, 1992). McDonough (1992) suggests adding 1 or 2 mixing elements to the static mixer if the injection is not in the center of the pipeline to allow for the extra mixing needed to make up for the injection deficiency. Pahl an Muschelknautz (1982) state that, in practice, 15 - 20 percent is added to the total length of the mixer when feed at the side is preferred.

**Droplet Size and Dispersion.** The theory relating particle destabilization to turbulent eddy sizes developed by Amirtharajah and Trusler (1986) was presented previously in the "Effects of Mixing on Coagulation" section of this chapter. Several researchers have focused their efforts on determining droplet size and dispersion in turbulent pipe flow through static mixers. Berkman and Calabrese (1988) studied the dispersion and mean droplet size of viscous oils in water mixed by a 24 element Kenics static mixer at Reynolds numbers of 12,000, 15,000, 18,000 and 21,000. They stated that "In static mixers, the largest eddies are of order of 0.5 D while the smallest eddies are of order η (the Kolmogoroff microscale)." Because the maximum stable drop sizes are much larger than the microscale, they concluded
that the inertial subrange applies in static mixers. Their results correlated well with the equation:

\[ D_{\text{MAX}} = 1.5 \, D_{32} \]  

(2.10)

where \( D_{\text{MAX}} \) is the maximum stable drop size at the exit of the static mixer and \( D_{32} \) is the Sauter mean diameter which can be calculated using the equation:

\[
\frac{D_{32}}{D} = C_6 \, \text{We}^{-3/5} \, f^{-2/5} \left[ 1 + C_7 \, f^{1/3} \, V_i \left( \frac{D_{32}}{D} \right)^{1/3} \right]^{3/5}
\]  

(2.11)

where \( C_6 \) and \( C_7 \) are empirical constants. The Weber number, \( \text{We} \), the Fanning friction factor, \( f \), and the viscosity group, \( V_i \), are given below.

\[ \text{We} = \rho u^2 D / \xi \]  

(2.12)

\[ f = (\Delta P \, D) / (2L \, \rho u^2) \]  

(2.13)

\[ V_i = (\mu_d / \xi) (\rho / \rho_d)^{1/2} \]  

(2.14)

\( \xi \) is the interfacial tension, \( \mu_d \) is the viscosity of the dispersed phase, and \( \rho_d \) is the density of the dispersed phase. For \( \text{Re} > 12,000 \), \( f \) is constant and is equal to 0.416. Taking this into account, the empirical constants were determined to be \( C_6 \, f^{-2/5} = 0.49 \) and \( C_7 \, f^{1/3} = 1.38 \).

Taweel and Walker (1983) performed experiments with kerosene and water using a Lightnin In-Liner static mixer with various numbers of elements in various configurations over a range of Reynolds numbers from approximately 12,000 - 27,000. They found that after a certain amount of mixing a dynamic equilibrium is achieved where the rate of dispersion is
equal to the rate of coalescence resulting in an equilibrium droplet size, $D_{32}$. They go on to say that the use of elements beyond the number needed to achieve that equilibrium only serves to maintain the equilibrium. Thus, no more mixing is achieved beyond a certain point. They also found that the rate at which the equilibrium value of $D_{32}$ was achieved, as well as the equilibrium value $D_{32}$ itself, was strongly dependent on $\epsilon$, the energy dissipation per unit mass within the static mixer. They present the equation:

$$\frac{D_{32}}{D_h} = K \text{We}^{-0.6} f^{-0.4}$$

(2.15)

to be used to calculate the Sauter mean diameter, where $\text{We}$ and $f$ are defined in equations 2.12 and 2.13 previously, $K$ is a proportionality constant dependent on the viscosity of the emulsion, and $D_h$ is the hydraulic diameter of the mixing element channels. From these two studies, a possible method for calculating the size of the inertial subrange eddies generated in the static mixer can be developed and related to the work of Amirtharajah and Trusler (1986) for further exploration of their theory.

**Energy Dissipation in the Static Mixer.** A parameter typically used in the water treatment industry when designing a rapid mixing process is the G-value. The G-value is a measure of the rate of energy input per unit volume of a given reactor. The equation used to calculate the G-value is equation 2.3. One of the problems inherent with the use of the G-value parameter for a static mixer is the calculation of the volume through which the turbulent energy is dissipated. Some would argue that the turbulence generated by the static mixer does not end at the mixer exit but continues for some unknown distance downstream. Thus, the designer does not know what volume to use in the G-value calculation.
Another problem with the G-value is the comparison between the static mixer and other mixing configurations such as the backmix reactor or in-line blender. These types of mixers usually have high zones of turbulence localized around the impellers and the G-values calculated for them are usually an average number, taking the entire reactor volume into account. Static mixers tend to have a more uniformly distributed turbulence throughout the mixer volume, and so the G-value applies as a more accurate measure of energy input throughout the mixer volume. It is possible that average G-value ranges which are to be avoided with other types of mixers may be satisfactory when using a static mixer.

McDonough (1992) presents the equation for calculating G-value in water treatment as follows:

$$G = 188.6 \sqrt{\frac{f_D u^3 C_f}{D}}$$  \hspace{1cm} (2.16)

where $f_D$ is the Darcy friction factor and $C_f$ is a flow coefficient based on the Reynolds number. It should be noted that this equation and others presented by McDonough appear to have been developed for a particular type of static mixer which is not stated in his book. These equations may or may not be valid for other types of static mixers.

Several researchers (Taweel and Walker, 1983; Meyer et al., 1988; Berkman and Calabrese, 1988; Schutz, 1988; Bourne and Maire, 1991; Bourne et al., 1992) use the following expression for calculating the energy dissipation rate per unit mass, $\epsilon$, in the static mixer:
This equation seems to be valid under all turbulent conditions and is a possible replacement for the G-value in water treatment when considering static mixers.

Bourne and Maire (1991) go on to further break down the energy dissipation rate $\varepsilon$ using the equation:

$$
\varepsilon = \frac{\mu \Delta P}{\rho L_{SM}} \quad (2.17)
$$

where $\psi$ is the turbulent dissipation caused by gradients of the turbulent velocity fluctuations and $E_D$ is the direct dissipation due to gradients of the mean velocity. Bourne and Maire (1991) imply that only a certain percentage of the total energy dissipated will have an influence on micromixing, that percentage being the turbulent dissipation, $\psi$. Bourne et al. (1992) state that "the static mixer with the more open structure was the better generator of turbulence and made the most use of the pressure drop".

Taweel and Walker (1983) show a linear relationship between increasing energy dissipation rates and decreasing average drop diameter, thus showing a better mixing quality at higher energy dissipation rates. They also point out that increasing the number of mixing elements does not substantially alter the intensity of turbulence at a given flow velocity, but merely sustains this level of turbulence for a longer period of time. This is particularly relevant if $\varepsilon$ is considered a measure of turbulence intensity within the mixer, because, as it
Kabatek et al. (1989) present the equation:

\[ \Pi_c = \lambda_{\text{eq}} \text{Re} \left( \frac{L_{\text{eq}}}{D} \right)^2 \]  

(2.19)

for use in comparing the energy demands of homogenization for various types of static mixers. They state that this parameter (\(\Pi_c\)) includes both the homogenization effects as well as the pressure drop and provides an overall picture of the static mixer efficiency. Their experimental results, however, do not get far enough into the turbulent flow range to be of much use in this research.

**Measures of Mixing Quality.** One of the most difficult parameters to assess, both in static mixers and in other water treatment mixing processes, is the mixing quality produced by the static mixer. Researchers have tried several different ways of examining the homogeneity of the solutions mixed within the static mixer including: visual observation of color dyes, measuring quantities of undesired products in the final mixed water, performing tracer tests with Rhodamine dye, high speed photographs of static mixer effluent, and measuring the conductivity of static mixer effluent at several points on a grid while injecting concentrated sodium chloride. All of these methods will work, but some are better for a given application than others. The visual, undesired products, and conductivity methods are adequate for working on a laboratory scale when the primary focus is on chemical dispersion. The photographic method is good for analyzing droplet sizes and dispersion in the laboratory. The Rhodamine dye tracer tests, however, are more suited to a full scale plant test. Before
any analysis is performed on a static mixer, the experimental method should be chosen carefully so that the most useful results will be obtained.

As mentioned previously, the variation coefficient presented in equation 2.4 is a commonly used parameter for evaluating the homogeneity of the mixed solution produced by the static mixer. As is the case for laminar flow, the well mixed condition is represented by the value $C_v = 0.05$. However, this parameter is not always the best one to use because typically some information on how well the static mixer mixes, such as $\sigma$, must already be known. If the research starts with no prior knowledge of the mixing ability of the static mixer, detailed measurements must be taken so that a suitable standard deviation can be developed. Pahl and Muschelknautz (1982) propose the following equation for two quantities related to each other through volumetric flow rate:

$$\frac{S_1}{C_{V1}} = \frac{\sqrt{Q_2}}{Q_1} \frac{S_1}{\sigma_0} \quad (2.20)$$

where:

$$C_{V1} = \frac{1}{n} \sum_{i=1}^{n} C_{V1,i} \quad (2.21)$$

$$C_{V1,i} = \frac{Q_{1,i}}{(Q_{1,i} Q_{2,i})} \quad (2.22)$$

$$S_1^2 = \frac{1}{n-1} \sum_{i=1}^{n} (C_{V1,i} - \overline{C_{V1}})^2 \quad (2.23)$$

$$\sigma_0 = [C_{V1}(1-C_{V1})]^{0.5} \quad (2.24)$$
n = number of samples

Q_{1,i} = volumetric flow rate of component 1, sample i

Q_{2,i} = volumetric flow rate of component 2, sample i

S_1 = standard deviation of several repeated measurements of component 1

\sigma_0 = initial standard deviation

\frac{S_1}{C_{v1}} = variation coefficient for component 1

S_1/\sigma_0 = relative standard deviation of component 1

Pahl and Muschelknautz (1982) also suggest the use of the equation:

\frac{S_1}{C_{v1}} = a \exp \left( - \frac{L_{SM}}{D} \right) \tag{2.25}

for expressing the results in a mathematical form and graphing the variation coefficient versus \( L_{SM}/D \). They were able to use the above equations in the analysis of "conductivity type" experimental results for five types of static mixers which were tested (Sulzer SMX, Hi-Mixer, Kenics, Komax, and Lightnin). They found that the Sulzer and Hi-Mixer produces the most homogeneous solution at the lowest \( L_{SM}/D \) ratio.

Godfrey and Amirtharajah (1991) made a slight modification on an experimental equation developed for Sulzer SMV static mixers and proposed the equation:

\frac{\sigma}{\sigma_0} = 2 \exp (-1.54 f^{0.5} L_{SM}/D) \tag{2.26}
where \( \sigma/\sigma_0 \) is the relative standard deviation and \( f \) (equation 2.13) is a friction factor specific to a given static mixer. They found that this equation produced numbers for \( L_{SM}/D \) within the same order of magnitude of the experimental results for the Sulzer mixer indicated. The authors indicated that they feel this equation could possibly be used as a generic equation for static mixers.

**Summary**

Laminar and turbulent flows are the two types of flow to be considered when working with static mixers. Although laminar flow is fairly common in the chemical process industry it is rarely, if at all, seen in the water treatment field. The primary type of flow of interest to water treatment engineers is turbulent flow. Static mixers are attractive in the water treatment industry because of their short residence times in combination with their high intensity mixing capabilities. This combination ensures fast micromixing with very little backmixing in the plug flow configuration of the static mixer. Another important quality of the static mixer is the low operation and maintenance costs. When designing the static mixer, the important parameters to consider are: pressure loss across the mixer, detention time within the mixer, number of mixing elements, introduction of the fluids to be mixed, energy dissipation in the mixer, and final mixed water quality.
CHAPTER III

MATERIALS, EQUIPMENT, AND PROCEDURES

The static mixer is an in-line type mixer, and therefore, it is much more difficult to use when conducting batch type experimental tests. The mixer must have a continuous flow of fluid going through it or no mixing will occur. Thus, the experimental procedures used when evaluating a static mixer must combine the continuous flow aspects of the mixer with the batch reactor type jar tests which are typically used in coagulant and mixing evaluation in the laboratory. This was accomplished by setting up a continuous flow mixing loop.

This loop could be continuously recycled when the experiment was being set up and no coagulant was being added. Then, the process line could be diverted to the batch type flocculation reactors when coagulant addition began. Typically, between these two steps, the process flow was diverted to a waste container for a short period to allow time for the fresh coagulant flow to enter the flow stream and reach the process line exit. In this way, a series of hybrid batch type experiments were conducted to evaluate the mixing performance of the static mixer. After flocculation, the water was either allowed to settle or was poured directly into a filter with no settling.

A batch type filter column was used to simulate direct filtration. This configuration was used because, like the static mixer, a filter normally operates under continuous flow conditions. This requires large amounts of water which are not easily generated in the
laboratory. The batch or jar filtration technique employed in these experiments was
developed by Brink et al. (1988). The direct filtration technique was used because it was
thought that the static mixer would more readily show the effects of any differences in mixing
intensity if the coagulation mechanism used was charge neutralization, which is typical of the
direct filtration approach.

**Experimental Procedure**

The tests performed were carried out using an artificial water prepared in the
laboratory with tap water. The coagulant used for treatment of the water was aluminum
sulfate. Sodium hydroxide was used to adjust the pH when needed. The artificial water was
measured out in a quantity of 7 liters and poured into an 8-inch x 8-inch x 8-inch Nalgene®
holding tank. In this tank, sodium hydroxide was added and mixed by a Lightnin LabMaster
mixer, model TS2010 (The General Signal Corp., Avon, N.Y.), for approximately 30 seconds
at 600 rpm. Next, the process flow and chemical feed pumps were started, and treated water
was wasted for an appropriate amount of time, based on detention time in the total length of
process tubing at a given flow rate. This wasting was done to allow the volume of water
already in the tube sufficient time to exit and to ensure that the treated sample was fresh.

**Rapid Mixing**

The flow path of the process flow can be seen in Figure 3.1. The water was pumped
from the raw water holding tank through approximately 43 inches of ½-inch inside diameter
Tygon® tubing and then entered a tube tee where the upstream tap for the Omega PX154
Figure 3.1. Experimental Setup for Rapid Mixing in a Static Mixer
series pressure transducer (Omega Engineering, Inc., Stamford, CT.) was connected. The process flow pump was an FMI Lab Pump, model QD-3 (Fluid Metering, Inc., Oyster Bay, NY.), which had a maximum capacity of 2.3 L/min. The water then flowed through another tube tee where the coagulant feed line was tied into the process flow stream. The coagulant feed line consisted primarily of \( \frac{1}{8} \)-inch inside diameter Tygon® tubing, except for the section of tubing that actually went into the tube tee. This section of tubing had some very small diameter tubing (approximately \( \frac{1}{16} \)-inch inside diameter) inserted within it to allow for a constant chemical injection flow stream, as opposed to just a drip, at low chemical feed rates. The chemical feed pump was an FMI Lab Pump, model QD-1 (Fluid Metering, Inc., Oyster Bay, NY.). The water then entered the Komax Motionless Mixer, model 500-016 (Komax Systems, Inc., Wilmington, CA.), where the rapid mixing treatment process under investigation actually occurred. The Komax mixer was a \( \frac{1}{2} \)-inch inside diameter, stainless steel tube with 8 mixing elements. After leaving the static mixer, the water passed through another tube tee where the downstream tap for the Omega pressure transducer was connected. From this tee, the water passed through approximately 11.5 inches of \( \frac{1}{2} \)-inch inside diameter Tygon® tubing and finally exited through a 90° tube elbow into the 4-liter waste container.

**Flocculation**

As stated previously, the water was wasted for a period of time sufficient to flush out any water remaining from a previous test. The flow stream was then diverted by hand into one of two Phipps and Bird 2-liter square jars (The General Medical Corp., Richmond, VA.). One of the samples in the jars was used for the purpose of settling the treated water, while
the other was used for conducting a direct filtration test. Both samples were simultaneously flocculated using the Phipps and Bird HS-4 Stirrer, model 7790-100 (The General Medical Corp., Richmond, VA.). A sketch of the Phipps and Bird stirrer along with the jar layout can be seen in Figure 3.2. The first jar was filled to just above the top of the paddle, and then the process flow line was moved to the second jar. When the second jar was also filled to just above the paddle, the stirrer was started to minimize lag time between rapid mixing and flocculation. The two jars were then filled to the 2-liter mark on the containers. The process flow line was moved alternately from one jar to the other to and keep the conditions in each jar as similar as possible. When the water level reached the 2-liter mark in both jars, the flocculation time period was begun. This was also the point at which a sample was taken from the process flow line for use in measuring zeta potential, using the Zeta Meter (Zeta Meter, Inc., New York, NY.). The samples were flocculated at 64 rpm for 4 minutes and then at 45 rpm for 4 minutes. These paddle speeds corresponded to G-values of 60 sec\(^{-1}\) and 40 sec\(^{-1}\), respectively, according to studies done by Hudson (1980) for the 2-liter square jars. A graph showing velocity gradient versus rpm for the 2-liter square jars is shown in Figure 3.3.

**Settling and Filtration**

After the water was flocculated for the specified amount of time, the stirrer was turned off, and the jars were removed. The settled water jar was immediately placed in a location where it would not be disturbed, and an 80-ml sample was drawn from the sample tap near the bottom of the jar to measure mixed water pH. The pH was measured using a Fisher Accumet pH meter, model 144 (Fisher Scientific Co., Pittsburgh, PA.). The
Figure 3.2. Phipps and Bird HS-4 Stirrer with 2-liter Square Jars

Figure 3.3. Velocity Gradient vs. rpm for a 2-liter Square Jar Using a Phipps and Bird Stirrer (Hudson, 1981)
other jar was used for the direct filtration process. Samples were drawn from sample tap in the settled water jar after 20 and 35 minutes of settling time. The turbidity of these samples was immediately measured using the Hach Ratio Turbidimeter, model 18900-00 (Hach Chemical Co., Loveland CO.).

**Filter Column Description.** The filter column itself consisted of a 2¼-inch glass column with piping attached to the top and bottom to allow for inlet and outlet connections. A drawing of the filter column and the associated piping and valves can be seen in Figure 3.4. Backwash inlet and outlet connections were supplied as well as a separate filter effluent connection. A pump was used to regulate the flow through the filter so that constant rate filtration could be simulated. The filter pump was an FMI Lab Pump, model QD-1 (Fluid Metering, Inc., Oyster Bay, NY.). The flow rate of the filter effluent was approximately 70 ml/min. which gives a corresponding filtration rate of 0.67 gpm/ft². The filter media consisted of 18 inches of anthracite coal (E.S. = 1.0 mm, U.C. = 1.5) and was supported by a 6-inch graded gravel bed. The anthracite filter was used because it was thought that it would better simulate a true filtration process and magnify any deficiencies in the mixing capabilities of the static mixer.

**Filter Preparation.** When performing the direct filtration aspects of these experiments, the jar-filtration method developed by Brink et al. (1988) was used with some minor modifications. First, after the backwashing of the filter was completed, the backwash water remaining above the filter media was drawn down to a level just above the top of the media. This was done at the same rate at which the filter was normally run. When the water level reached the top of the media, 500 ml of deionized water were poured into the filter.
Air Bleed Off Valve
Removeable Fitting

Backwash Water Out

2-1/4 inch I.D. Glass Filter Column

18-inch Anthracite Coal Filter Bed

6-inch Graded Gravel Support Layer

Backwash Water In

Ball Valves

Filter Regulating Pump

Filter Effluent

Figure 3.4. Filter Column Layout
column, through a funnel, with care taken to keep media disturbance at a minimum. The deionized water was also drawn down at the normal filtration rate to a level just above the media in preparation for the treated water sample to be added. Once the deionized water reached the proper level, the filter pump was turned off. The filter was prepared in this manner prior to any of the treatment steps described previously in the "Rapid Mixing" and "Flocculation" sections of this chapter.

**Filtration.** Immediately after the flocculation process was completed, the direct filtration jar was held by hand at a point just above the filter column. The treated sample in the direct filtration jar was allowed to flow through the sample tap near the bottom of the jar and down the inside of the glass filter column. Once the column was filled to about half of the clear space above the top of the filter media, the filter pump was started, and the column was then filled to the top. A stop watch was also started simultaneously with the filter pump to monitor the filtration time interval. This also marked the starting point for the 20 and 35-minute intervals used for the settled water measurements.

The sample water was continuously filtered for 30 minutes, during which time the column was refilled approximately every 5 minutes until all of the sample was used. Before each refill, the water in the 2-liter sample jar was gently agitated with a glass rod stirrer to resuspend any floc that had settled during the 5-minute waiting interval and ensure that the water being poured into the filter was of uniform quality. After 26 minutes and 45 seconds, the first filtered water turbidity sample was taken. Approximately 30 seconds was needed to collect enough sample for measurement in the Hach Ratio Turbidimeter. This first sample was nominally designated as the 27-minute sample. Filtered water samples were also taken.
at 28, 29, and 30 minutes, using the same nominal designation. Once the turbidity of the 30-minute sample was measured, this sample was then used for a particle count measurement on the Brinkmann Particle Size Analyzer (Brinkmann Instrument Co., Westbury, NY.).

**Backwashing.** The final step of the experimental procedure was to backwash the filter in preparation for the next test. The backwash line going into the bottom of the filter was connected to a potable water faucet, and the water was turned on and set at a flow rate of approximately 3 L/min, which gave a filter bed expansion of 30 percent. The water was backwashed until the backwash effluent turbidity fell below 0.5 ntu. The backwash time was usually about 20 minutes. If the previous experiment had been completed on a different day, then the filter was backwashed for about 5 minutes to eliminate any settling of the media that may have occurred and to ensure identical starting conditions for each test.

**Zeta Potential Measurements**

A measurement of electrophoretic mobility using the Zeta Meter was used to determine the zeta potential of a particle in a suspension. The Zeta Meter is operated by taking a sample of the water to be measured and pouring it into a cell consisting of two reservoirs connected by a thin tube to allow free passage of water from reservoir to reservoir. The cell has a platinum-iridium cathode and an anode across which a DC power supply is connected to supply a voltage to the water. When the power supply is activated, the particles are attracted to either the positive or negative terminal depending on the charge of the particles. By using a microscope and the proper illumination, the amount of time it takes for the particles to travel across a grid is measured with a stopwatch. Using this measured time, the voltage applied, the temperature of the sample, and the magnification of the microscope,
the electrophoretic mobility, and thus, zeta potential can be determined with a nomograph supplied by the manufacturer.

**Particle Size Measurements**

Particle size measurements were taken on a number of filtered water samples. However, not all of the filtered water samples could be analyzed because some were below the detection limit of the Brinkmann Particle Size Analyzer. The particle size analyzer operates with a rotating laser beam and a photodetector. The laser beam is rotated at a high frequency to negate any motion of the particles. Simultaneously, it is scanned within a measurement cell area. A pulse is generated in a photocell due to the beam-particle interaction, and the characteristics of the pulse are used to determine the size of the particle. The width of the pulse represents the time of interaction as the laser beam crosses the surface of the particle. The height of the pulse represents the reduction in intensity of light reaching the detector as a result of the interaction. The pulse width is used directly to determine the size of the particle.

**Setting the Pump Flow Rates**

Normally, before each experiment, the process flow and chemical feed pump flow rates had to be set at a different rate than the previous test. This procedure usually involved several iterations of measurements to obtain the desired headloss and dosage accuracies. First, the process flow pump was set at an appropriate flow rate to obtain the desired headloss for the particular experiment about to be conducted. Next, the chemical feed pump rate was set based on the process flow pump rate. Usually, the process flow pump rate was set a little
lower than what was required to achieve the desired headloss. This was done to account for the chemical feed pump flow rate, which had not yet been added to the flow stream. A rough idea of where the process flow should be set at for a given headloss was obtained using a curve developed previously with the in-line static mixer. This curve was based on measurements taken using the differential pressure transducer and measured flow rates. The flow rates were converted to velocities based on a ½-inch inside tube diameter, and then a plot of headloss versus velocity head ($v^2/2g$) was made. This plot can be seen in Figure 3.5. The curve in Figure 3.5 was also used to extrapolate headloss values at higher flow rates, which were above the 0 - 25 inches of water column range of the pressure transducer.

To set the process flow pump, a volumetric flow rate was taken. This was done by first keeping the process line in a continuous return flow loop, in which the water being pumped was recycled back to the raw water holding tank. To take a measurement, the process flow line was diverted by hand into a 4-liter container while simultaneously starting a stopwatch. After a sufficient sample was taken, the process flow line was diverted back to the raw water holding tank while simultaneously stopping the stopwatch. The volume collected was poured into a 2-liter graduated cylinder, and a measurement was made. Using the time interval on the stopwatch and the total volume collected, a flow rate was calculated.

To set the chemical feed pump, a similar volumetric flow procedure was used, except that the sample was collected directly in the 10 ml graduated cylinder being used to make the measurements. The desired chemical feed pump rate was calculated based on the desired dosage and the process flow pump rate already determined. A spreadsheet containing the necessary information was developed to aid in the calculation process. Once the desired flow
Figure 3.5. Headloss vs. Velocity Head for Experimental Static Mixer
rate for each pump was achieved, three measurements were taken for each pump to ensure repeatability. These measurements were typically within +/- 1 percent of each other. An average of these three measurements was used for the chemical dosage calculations. It should be noted that each time a measurement was made on either pump, the pump was turned off, allowed to come to a complete stop, and then turned back on. This was done to ensure that the flow rate did not change appreciably when the pump was turned off and on.

**Preparation of Raw Water**

The artificial raw water used for these tests was prepared by mixing dried bentonite clay with tap water. The raw water was made in 50-liter batches, allowed to settle, and then diluted to the desired turbidity for testing. Using the calibration curve in Figure 3.6, developed by Nouvel (1992), a concentrated suspension of bentonite clay water was made to achieve a desired residual turbidity. The supernatant having the desired residual turbidity in suspension was siphoned off into another container. This water was then diluted and used as the final test water. The average particle diameter in this final test water was determined to be approximately 1 µm using the Brinkmann Particle Size Analyzer.

**Procedure**

Typically, 10 g of dried bentonite clay supplied by Fisher Scientific Co. (Pittsburgh, PA.) was added to about 3 liters of tap water, and this suspension was mixed thoroughly using a small laboratory mixer. This created a super-concentrated slurry of bentonite clay which was then poured into a large plastic container and diluted to a total volume of 50 liters. Once the container was full, the water was thoroughly agitated to ensure that a uniform
suspension was created. This was accomplished by tipping the container on its side and rolling it around in such a way as to create good mixing action. The container was then moved to a counter top and allowed to settle for 24 hours.

After the 24 hour settling period, a second container of equal size was placed on the floor below the first container and a length of tubing was used to siphon off the supernatant down to a depth of around 2 inches from the bottom of the first container. It should be noted here that extreme care was taken not to disturb, in any way, the clay particles that had already settled out on the bottom of the container. The first container was then rinsed out thoroughly, and the supernatant water was divided equally between the two containers. Typically, at this point, the turbidity was approximately 25 ntu; however, a final turbidity of 13 ntu was desired. The next step was to dilute the supernatant to a point where it was uniformly 13 ntu. Tap water was added to each container in equal amounts, the container
was thoroughly mixed, and then the turbidity was checked. This process was repeated until a 13 ntu reading was obtained for each container. The raw water was agitated before each test volume was poured from the container to resuspend any particles that had settled during intervals between testing.

**Raw Water Measurements**

Once the desired 13 ntu water was obtained, some general raw water parameters were measured. The pH of the water was measured using the Fisher Accumet pH meter. Conductivity of the water was measured using a YSI Model 32 Conductance Meter (Yellow Springs Instrument Co., Inc., Yellow Springs, OH.). Zeta potential of the raw water was measured using the Zeta Meter, and a particle count measurement was taken on the Brinkmann Particle Size Analyzer. Raw water alkalinity was measured using the method outlined in Standard Methods (# 2320, 1992). These five parameters remained relatively constant based on periodic checks for the duration of use of a particular batch of raw water. Temperature was measured each day on which an experiment was conducted. Some typical raw water quality parameters were: turbidity = 13 ntu, pH = 7.3, specific conductivity = 80 μmho/cm, temperature = 21° C, zeta potential = -12.5 mV, alkalinity = 15 mg/L as CaCO₃, and particle count = 3,000,000/ml.

**Treatment Chemical Preparation**

Two chemicals were used in these tests. Aluminum sulfate was used as the coagulant, and sodium hydroxide was used for any necessary pH adjustment. Aluminum sulfate was selected because it is a common coagulant used throughout the water treatment industry.
Sodium hydroxide was used because it is easy to prepare and maintain in a laboratory setting.

**Aluminum Sulfate**

The first chemical solution prepared was the metal salt coagulant, aluminum sulfate (alum). Due to the limitations of the chemical feed system, a low concentration of aluminum sulfate was used to allow the use of higher chemical feed rates. The concentration of this solution was 500 mg/L as $\text{Al}_2(\text{SO}_4)_3 \cdot 14.3 \text{ H}_2\text{O}$. The aluminum sulfate crystals used were supplied by EM Science (EM Industries, Inc., Cherry Hill, NJ.) and were assayed as $\text{Al}_2(\text{SO}_4)_3 \cdot 16 \text{ H}_2\text{O}$. To calculate the actual weight of aluminum sulfate crystals needed, the desired weight of $14.3 \text{ H}_2\text{O}$ aluminum sulfate was multiplied by a ratio of the molecular weights of $16 \text{ H}_2\text{O}$ aluminum sulfate and $14.3 \text{ H}_2\text{O}$ aluminum sulfate. This ratio was $631/600$, or 1.0517. For example, if a concentration of 500 mg/L as $\text{Al}_2(\text{SO}_4)_3 \cdot 14.3 \text{ H}_2\text{O}$ was desired in 1 liter of solution, then the weight of aluminum sulfate as $\text{Al}_2(\text{SO}_4)_3 \cdot 16 \text{ H}_2\text{O}$ that would be required would be $500 \text{ mg} \times 1.0517 = 525.8 \text{ mg}$.

After the proper amount of aluminum sulfate had been weighed out, the crystals were poured into a 2-liter volumetric flask filled to about 80 percent capacity with deionized water. This flask was then capped and shaken vigorously until no more aluminum sulfate crystals could be seen. The flask was then filled to the 2-liter mark and was again shaken to ensure that the solution was uniformly mixed. Aluminum sulfate solutions were made fresh on a regular basis and never used if more than one week old.

**Sodium Hydroxide**

The second chemical solution prepared for these experiments was a sodium hydroxide solution. This solution was used for pH adjustment when needed. Typically, a 0.01 M
solution of sodium hydroxide was prepared for all tests. This solution was prepared using standard techniques and did not require any special calculations. Sodium hydroxide solutions were prepared when needed and never used if more than two weeks old.

**Preliminary Jar Testing**

Some preliminary jar testing was done to determine optimum treatment conditions (alum dose and pH) for the bentonite clay raw water. These jar tests were conducted using standard jar testing protocol and the Phipps and Bird equipment described in the "Experimental Procedures" section of this chapter.

**Standard Jar Tests**

Two series of jar tests were done at a dose of 20 mg/L of alum with varying pH values to first determine the optimum pH. Next, two series of tests were done at the optimum pH with varying coagulant dosages to determine the optimum alum dosage. For all of these tests, the rapid mixing was done at a speed of 100 rpm for a duration of 30 seconds. The corresponding G-value from Figure 3.2 was 110 sec$^{-1}$. These samples were flocculated with three stages of mixing as opposed to the two-stage mixing used in the static mixer tests. The mixing speeds for each stage were 64 rpm, 45 rpm, and 25 rpm, corresponding to G-values of 60 sec$^{-1}$, 40 sec$^{-1}$, and 20 sec$^{-1}$, respectively, from Figure 3.2. The third stage was added to make better floc for settling. The duration of each flocculation stage was 6 minutes. Two settled water samples were taken, one at 20 minutes and one at 35 minutes, and these data were used to determine the optimum treatment conditions.
**Jar Filtration Tests**

Another set of five jar filtration tests were also performed using the backmixing type rapid mix configuration of the standard jar tests. These tests were performed to evaluate the optimum dosage for direct filtration. The pH was held constant for these tests. The rapid mixing was done at 100 rpm for 30 seconds, but only two stages of flocculation were used at speeds of 64 rpm and 45 rpm for 4 minutes each. Two samples were prepared at each dosage, one to be settled and the other to be filtered. The settled water was sampled after 20 and 35 minutes of settling time. The filtered water sample was handled as described previously in the "Experimental Procedures" section of this chapter. Backwashing of the filter was done as described previously.

**Full Scale Treatment Plant Survey**

A survey of surface water treatment plants currently using a static mixer as the rapid mixing unit was taken so that a comparison of the experimental results could be made with actual plant data. This survey would also provide a mechanism for observing similarities between static mixers already designed and in place. The information on which plants have static mixers was supplied by the American Water Works Association using a data base which was put together several years ago and has been updated periodically since then. A copy of the survey form can be seen in Appendix A. The survey was designed primarily to find some basic information on the treatment plant as well as information on the static mixing unit. A few opinion type questions were also asked.
CHAPTER IV

RESULTS AND DISCUSSION

Preliminary jar tests were performed to determine the optimum treatment conditions for coagulation of the bentonite clay water. Tests were then done at the optimum treatment conditions as well as poor treatment conditions, using the static mixer as the rapid mixing process. Finally, the treatment plant data collected with the static mixer survey are presented and evaluated with some comparisons to experimental results. This forms a link between full scale facilities, and the laboratory work done for this thesis. The main sections are divided as follows: jar test data, static mixer experimental results, and full scale plant survey data.

Jar Test Data

Four series of standard jar tests were performed to determine the optimum treatment pH and coagulant dosage for the artificial bentonite clay water. This was done because it was necessary to determine the chemical conditions under which the best coagulation would occur. Once the ideal conditions are known, it is easier to empirically evaluate the rapid mixing process in the static mixer at both the optimum chemical conditions and at poor chemical conditions. Typically, the chemical conditions have a much greater influence on coagulation than the mixing process, thus making it more difficult to evaluate a given rapid mixing process. The physical rapid mixing and flocculation conditions used for these jar tests,
such as G-value and detention times, were selected with the intention of producing the best possible settled water.

**Optimum pH Determination**

The first series of jar tests was performed at a dosage of 20 mg/L over a broad range of pH values. The 20 mg/L dosage was selected because it was considered to be more than adequate to treat the 13 ntu bentonite water. Eight pH values were tested ranging from 5.68 to 7.43 at roughly 0.2 - 0.3 pH unit intervals. Table 4.1 shows the results of these tests. A plot of the data from Series 1, seen in Figure 4.1, was used to determine the pH range that should be more closely evaluated. It was determined that the next series of tests should be conducted in the pH range of 6.9 - 7.9.

The next series of tests was also performed at a coagulant dosage of 20 mg/L but over a narrower pH range than the first series of tests. The actual pH range was from 6.9 - 7.88 at 0.10 - 0.15 pH unit intervals. Data for Series 2 can be seen in Table 4.1. From the graph presented in Figure 4.2, it can clearly be seen that the optimum pH range is 7.1 - 7.4, and more specifically the optimum pH for the best settled water is 7.25 based on the 35 minute settling time.

**Optimum Dosage Determination**

The next two series of tests were performed to determine the optimum coagulant dosage at a given pH. The dosage range for Series 3 was from 5 - 22.5 mg/L at 2.5 mg/L intervals, while the pH was in the 7.1 - 7.15 range. The data for Series 3 can be seen in Table 4.2 and are evaluated in Figure 4.3. Using the settled water turbidity after 35 minutes of
Table 4.1. Jar Test Results for Optimum pH Determination

**Series 1**
Alum Dosage = 20 mg/L

<table>
<thead>
<tr>
<th>Jar Number</th>
<th>pH</th>
<th>Turbidity at 20 minutes (ntu)</th>
<th>Turbidity at 35 minutes (ntu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.68</td>
<td>2.50</td>
<td>1.29</td>
</tr>
<tr>
<td>2</td>
<td>6.00</td>
<td>3.30</td>
<td>1.42</td>
</tr>
<tr>
<td>3</td>
<td>6.33</td>
<td>4.10</td>
<td>1.72</td>
</tr>
<tr>
<td>4</td>
<td>6.65</td>
<td>3.90</td>
<td>1.66</td>
</tr>
<tr>
<td>5</td>
<td>6.82</td>
<td>3.10</td>
<td>1.36</td>
</tr>
<tr>
<td>6</td>
<td>7.06</td>
<td>3.60</td>
<td>1.29</td>
</tr>
<tr>
<td>7</td>
<td>7.28</td>
<td>2.30</td>
<td>0.93</td>
</tr>
<tr>
<td>8</td>
<td>7.43</td>
<td>2.50</td>
<td>1.27</td>
</tr>
</tbody>
</table>

**Series 2**
Alum Dosage = 20 mg/L

<table>
<thead>
<tr>
<th>Jar Number</th>
<th>pH</th>
<th>Turbidity at 20 minutes (ntu)</th>
<th>Turbidity at 35 minutes (ntu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6.90</td>
<td>1.95</td>
<td>0.90</td>
</tr>
<tr>
<td>2</td>
<td>7.00</td>
<td>1.40</td>
<td>0.69</td>
</tr>
<tr>
<td>3</td>
<td>7.09</td>
<td>1.80</td>
<td>0.61</td>
</tr>
<tr>
<td>4</td>
<td>7.26</td>
<td>1.27</td>
<td>0.44</td>
</tr>
<tr>
<td>5</td>
<td>7.41</td>
<td>1.20</td>
<td>0.50</td>
</tr>
<tr>
<td>6</td>
<td>7.56</td>
<td>1.20</td>
<td>0.55</td>
</tr>
<tr>
<td>7</td>
<td>7.72</td>
<td>2.20</td>
<td>1.35</td>
</tr>
<tr>
<td>8</td>
<td>7.88</td>
<td>6.20</td>
<td>4.30</td>
</tr>
</tbody>
</table>
Figure 4.1. Optimum pH Determination, Alum Dosage = 20.0 mg/L

Figure 4.2. Optimum pH Determination, Alum Dosage = 20.0 mg/L
Table 4.2. Jar Test Results for Optimum Alum Dosage Determination

<table>
<thead>
<tr>
<th>Jar Number</th>
<th>Alum Dosage (mg/L)</th>
<th>Settled Water Turbidity at 20 minutes (ntu)</th>
<th>Settled Water Turbidity at 35 minutes (ntu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.00</td>
<td>3.30</td>
<td>3.20</td>
</tr>
<tr>
<td>2</td>
<td>7.50</td>
<td>2.40</td>
<td>1.55</td>
</tr>
<tr>
<td>3</td>
<td>10.00</td>
<td>2.10</td>
<td>1.38</td>
</tr>
<tr>
<td>4</td>
<td>12.50</td>
<td>1.85</td>
<td>1.16</td>
</tr>
<tr>
<td>5</td>
<td>15.00</td>
<td>2.30</td>
<td>0.91</td>
</tr>
<tr>
<td>6</td>
<td>17.50</td>
<td>1.84</td>
<td>0.69</td>
</tr>
<tr>
<td>7</td>
<td>20.00</td>
<td>1.47</td>
<td>0.60</td>
</tr>
<tr>
<td>8</td>
<td>22.50</td>
<td>1.50</td>
<td>0.56</td>
</tr>
</tbody>
</table>

Series 4
pH = 7.3 – 7.4

<table>
<thead>
<tr>
<th>Jar Number</th>
<th>Alum Dosage (mg/L)</th>
<th>Settled Water Turbidity at 20 minutes (ntu)</th>
<th>Settled Water Turbidity at 35 minutes (ntu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12.50</td>
<td>2.40</td>
<td>0.91</td>
</tr>
<tr>
<td>2</td>
<td>15.00</td>
<td>1.65</td>
<td>0.63</td>
</tr>
<tr>
<td>3</td>
<td>17.50</td>
<td>1.62</td>
<td>0.50</td>
</tr>
<tr>
<td>4</td>
<td>20.00</td>
<td>0.94</td>
<td>0.50</td>
</tr>
</tbody>
</table>
Figure 4.3. Optimum Alum Dosage Determination, pH = 7.1 - 7.15

Figure 4.4. Optimum Alum Dosage Determination, pH = 7.3 - 7.4
settling time as a guide, it was determined that the optimum, or minimum, dosage required to produce the best possible settled water was 17.5 mg/L.

The final series of standard jar tests was performed to confirm the optimum dosage stated in the previous paragraph. The tests for Series 4 were performed from 12.5 - 20 mg/L at 2.5 mg/L intervals which is a smaller range than Series 3. The pH range for this series was 7.3 - 7.4. Figure 4.4 is a graphical representation of the Series 4 data in Table 4.2. From this graph, it can be confirmed that the optimum dosage is 17.5 mg/L.

Using the alum coagulation diagram (Figure 2.3), the optimum chemical conditions of pH 7.25 and a dosage of 17.5 mg/L are determined to be in the lower section of the sweep coagulation regime. It should be kept in mind when evaluating these data that the physical conditions under which these tests were performed were primarily selected to produce the best settled water quality. Because of these physical conditions, it is believed that the optimum chemical conditions presented above were influenced towards the sweep coagulation regime. This is significant because the research conducted with the static mixer was carried out using a direct filtration treatment approach which does not use settled water.

Typically, water treatment plants operating under the direct filtration treatment scheme with alum as a coagulant also operate using chemical conditions in the charge neutralization regime of the alum coagulation diagram. If the static mixer tests were performed using the optimum chemical conditions determined above, then the direct filtration scheme would not be truly simulated. It was determined that several jar filtration tests should be performed to further evaluate coagulant dosage using the direct filtration approach so that
the conflict with the standard jar tests could be resolved. It was hoped that from these direct filtration jar tests an optimum dosage for direct filtration could be determined.

Direct Filtration Jar Tests

A series of five jar filtration tests were performed to evaluate the optimum coagulant dosage using a direct filtration treatment approach. The dosages covered a range from 10 - 20 mg/L in 2.5 mg/L intervals. The pH values for these tests range from 7.3 - 7.4. The results of these five tests are presented in Table 4.3. Figure 4.5 shows a steady leveling of the 35 minute settled water turbidity curve similar to the results presented in Figures 4.3 and 4.4. If only these data were considered, it would once again be determined that the optimum dosage was 17.5 mg/L. However, if the filtered water results seen in Figure 4.6 are

<table>
<thead>
<tr>
<th>Table 4.3. Direct Filtration Jar Test Results for Optimum Alum Dosage Determination</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Direct Filtration Jar Tests</strong></td>
</tr>
<tr>
<td>pH = 7.3 - 7.4</td>
</tr>
<tr>
<td>Test Number</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>5</td>
</tr>
</tbody>
</table>
Figure 4.5. Direct Filtration Optimum Alum Dosage Determination Using Settled Water Turbidity, pH = 7.3 - 7.4

Figure 4.6. Direct Filtration Optimum Alum Dosage Determination Using Filtered Water Turbidity, pH = 7.3 - 7.4
considered, it can be concluded that equal filtered water quality is obtained at dosages of 12.5 mg/L and 20 mg/L. This indicates that when direct filtration treatment is used, a dosage of 12.5 mg/L may also be used in the pH range of 7.1 - 7.4 to obtain the same results as a 20 mg/L dosage. It seems that the 12.5 mg/L dosage is optimum if operating under direct filtration and charge neutralization conditions, while the 17.5 mg/L dosage is optimum if operating under sweep coagulation with conventional treatment.

**Static Mixer Experimental Results**

The results of the static mixer tests were evaluated using several parameters. Average filtered water effluent turbidity, settled water turbidity at 20 and 35 minutes after flocculation, and zeta potential were the main parameters used. Some particle count measurements were made on the filtered water, but these data are incomplete because several tests produced filtered water below the particle count detection limit. The primary focus of this research was to determine some useful design parameters to be used when considering a static mixer for water treatment. The results of the static mixer tests will be analyzed with this purpose in mind.

Five sets of data were produced at various pH values and coagulant dosages. Mixing performance was evaluated at both good and poor chemical conditions. This was done with the hope that the influence of mixing could be more easily observed at poor chemical conditions. To get a sense of the coagulation mechanisms involved, the chemical operating points for these experiments are plotted on the alum coagulation diagram in Figure 4.7. Experiments were conducted using headlosses ranging from 0.25 - 9.5 feet of water pressure.
Figure 4.7. Experimental Chemical Operating Points on the Alum Coagulation Diagram
head. Detention times varied from 0.46 - 2.4 seconds. The data sets will be presented both individually and collectively so that independent as well as side by side comparisons can be made. Also, some comparisons will be made between the static mixer and the backmix configuration used in the jar filtration tests. In addition, two experiments were conducted using an empty pipe as the rapid mixing process. These results will also be presented.

Finally, the data collected in the static mixer survey will be presented. An analysis of these data will be made to search for any general trends in the design of static mixers already in use. A comparison between the full scale plant data and the experimental data will be performed so that any conclusions drawn can be confirmed from two different sources.

**Individual Static Mixer Experiments**

12.5 mg/L Dosage. The first series of rapid mixing experiments using the static mixer was performed at an alum dosage of 12.5 mg/L. Ten experiments were carried out at this dosage with pH values ranging from 7.05 - 7.4 and pressure losses of 0.33 - 9.5 feet. However, seven of the ten experiments were within the pH range 7.16 - 7.33. The data for this series are presented in Table 4.4. Figures 4.8 - 4.11 are graphical presentations of the four main evaluation parameters versus headloss.

Figure 4.8 shows that there was little change in filtered water effluent quality across the entire range of pressure losses tested. This result is a good indicator that static mixers perform well across a large range of mixing intensities. The apparent aberrations in zeta potential seen in Figure 4.9 at 1.5 ft and 4 ft of headloss are possibly due to the elevated pH values at those points, thus showing the strong influence of chemistry on water treatment.
Table 4.4. Static Mixer Rapid Mixing Experiments, Alum Dosage = 12.5 mg/L

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Flow Rate (L/min)</th>
<th>Pressure Loss (inches of water)</th>
<th>pH</th>
<th>Average Filtered Water Turbidity (ntu)</th>
<th>Particle Count/mL</th>
<th>Average Zeta Potential (mV)</th>
<th>Settled Water Turbidity at 20 min. (ntu)</th>
<th>Settled Water Turbidity at 35 min. (ntu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H5</td>
<td>0.45</td>
<td>4.19</td>
<td>7.33</td>
<td>0.10</td>
<td>N/A</td>
<td>-5.30</td>
<td>2.60</td>
<td>1.35</td>
</tr>
<tr>
<td>H1</td>
<td>0.79</td>
<td>13.00</td>
<td>7.25</td>
<td>0.09</td>
<td>N/A</td>
<td>-4.10</td>
<td>2.50</td>
<td>1.60</td>
</tr>
<tr>
<td>H6</td>
<td>0.95</td>
<td>18.30</td>
<td>7.41</td>
<td>0.08</td>
<td>N/A</td>
<td>-6.30</td>
<td>2.00</td>
<td>1.21</td>
</tr>
<tr>
<td>H3</td>
<td>1.10</td>
<td>24.90</td>
<td>7.25</td>
<td>0.06</td>
<td>N/A</td>
<td>-2.50</td>
<td>2.60</td>
<td>0.97</td>
</tr>
<tr>
<td>H20</td>
<td>1.56</td>
<td>49.97</td>
<td>7.44</td>
<td>0.10</td>
<td>N/A</td>
<td>-6.40</td>
<td>2.80</td>
<td>1.35</td>
</tr>
<tr>
<td>H21</td>
<td>1.56</td>
<td>49.97</td>
<td>7.26</td>
<td>0.07</td>
<td>N/A</td>
<td>-2.70</td>
<td>4.60</td>
<td>1.95</td>
</tr>
<tr>
<td>H7</td>
<td>1.57</td>
<td>50.52</td>
<td>7.05</td>
<td>0.07</td>
<td>N/A</td>
<td>-3.70</td>
<td>2.30</td>
<td>2.10</td>
</tr>
<tr>
<td>H8</td>
<td>1.57</td>
<td>50.52</td>
<td>7.16</td>
<td>0.08</td>
<td>N/A</td>
<td>-1.20</td>
<td>3.00</td>
<td>1.22</td>
</tr>
<tr>
<td>H9</td>
<td>1.92</td>
<td>75.70</td>
<td>7.18</td>
<td>0.07</td>
<td>N/A</td>
<td>-3.60</td>
<td>2.50</td>
<td>1.00</td>
</tr>
<tr>
<td>H4</td>
<td>2.36</td>
<td>115.00</td>
<td>7.32</td>
<td>0.08</td>
<td>N/A</td>
<td>-4.90</td>
<td>2.40</td>
<td>1.38</td>
</tr>
</tbody>
</table>
Figure 4.8. Average Filtered Water Turbidity vs. Pressure Loss for 12.5 mg/L Dosage

Figure 4.9. Zeta Potential vs. Pressure Loss for 12.5 mg/L Dosage
Figure 4.10. Settled Water Turbidity at 20 min. vs. Pressure Loss for 12.5 mg/L Dosage

Figure 4.11. Settled Water Turbidity at 35 min. vs. Pressure Loss for 12.5 mg/L Dosage
Both settled water turbidity curves also show a relatively flat response to changing headloss and hence changing mixing intensity. Several experiments were run at 4 feet of headloss so that repeatability of results could be established. As the data show, similar results were obtained for all four experiments at this pressure loss, thus giving good repeatability of experimental data.

8.0 mg/L Dosage. The next set of experiments was carried out at an alum dosage of 8 mg/L with pH values of 7.14 - 7.38 and headlosses ranging from 0.33 - 8.5 feet. This was done to assess the mixing effects with poor chemistry conditions in the charge neutralization regime. The data for these experiments can be seen in Table 4.5 and are graphically presented in Figures 4.12 - 4.15. The filtered water and zeta potential curves show relatively little change across the entire range of experimental headlosses. However, when analyzing the settled water data in the 8 to 8.5 feet of headloss range, a wide variation in settled water quality occurred for several experiments which should have had similar results. This apparent aberration could possibly be due to experimental errors because of the difficulty in properly setting the chemical feed pump flow rate at the higher feed rates needed for these high head loss experiments.

5.0 mg/L dosage. Because the experiments at the 8.0 mg/L dosage did not show the sensitivity to mixing that was anticipated, a third set of experiments in the charge neutralization regime was undertaken. This set of experiments was conducted at an alum dosage of 5.0 mg/L with headlosses ranging from 1 - 8 feet and pH values from 7.20 - 7.29. The dosage of 5.0 mg/L was chosen because it was the minimum possible dosage which would give consistently repeatable results. This is known because three experiments were
### Table 4.5. Static Mixer Rapid Mixing Experiments, Alum Dosage = 8.0 mg/L

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Flow Rate (L/min)</th>
<th>Pressure Loss (inches of water)</th>
<th>pH</th>
<th>Turbidity (ntu)</th>
<th>Particle Count/mL</th>
<th>Zeta Potential (mV)</th>
<th>Settled Water Turbidity at 20 min. (ntu)</th>
<th>Settled Water Turbidity at 35 min. (ntu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H19</td>
<td>0.42</td>
<td>4.20</td>
<td>7.27</td>
<td>0.16</td>
<td>N/A</td>
<td>-8.20</td>
<td>6.10</td>
<td>2.80</td>
</tr>
<tr>
<td>H18</td>
<td>0.75</td>
<td>13.10</td>
<td>7.32</td>
<td>0.14</td>
<td>56000.00</td>
<td>-9.10</td>
<td>5.30</td>
<td>3.60</td>
</tr>
<tr>
<td>H17</td>
<td>0.90</td>
<td>18.40</td>
<td>7.26</td>
<td>0.19</td>
<td>76000.00</td>
<td>-7.50</td>
<td>5.70</td>
<td>3.50</td>
</tr>
<tr>
<td>H16</td>
<td>1.05</td>
<td>25.00</td>
<td>7.17</td>
<td>0.19</td>
<td>56000.00</td>
<td>-7.40</td>
<td>6.70</td>
<td>3.60</td>
</tr>
<tr>
<td>H15</td>
<td>1.56</td>
<td>49.85</td>
<td>7.26</td>
<td>0.12</td>
<td>23000.00</td>
<td>-6.50</td>
<td>5.55</td>
<td>3.00</td>
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<tr>
<td>H14</td>
<td>1.90</td>
<td>74.71</td>
<td>7.21</td>
<td>0.17</td>
<td>78000.00</td>
<td>-7.00</td>
<td>6.30</td>
<td>2.80</td>
</tr>
<tr>
<td>H11</td>
<td>2.19</td>
<td>99.13</td>
<td>7.38</td>
<td>0.13</td>
<td>39000.00</td>
<td>-8.00</td>
<td>7.60</td>
<td>4.30</td>
</tr>
<tr>
<td>H12</td>
<td>2.19</td>
<td>99.13</td>
<td>7.14</td>
<td>0.22</td>
<td>60000.00</td>
<td>-7.50</td>
<td>7.60</td>
<td>4.00</td>
</tr>
<tr>
<td>H13</td>
<td>2.19</td>
<td>99.13</td>
<td>7.34</td>
<td>0.15</td>
<td>55000.00</td>
<td>-8.00</td>
<td>5.60</td>
<td>3.20</td>
</tr>
<tr>
<td>H10</td>
<td>2.21</td>
<td>100.96</td>
<td>7.35</td>
<td>0.10</td>
<td>N/A</td>
<td>-6.50</td>
<td>2.60</td>
<td>1.40</td>
</tr>
</tbody>
</table>
Figure 4.12. Average Filtered Water Turbidity vs. Pressure Loss for 8.0 mg/L Dosage

Figure 4.13. Zeta Potential vs. Pressure Loss for 8.0 mg/L Dosage
Figure 4.14. Settled Water Turbidity at 20 min. vs. Pressure Loss for 8.0 mg/L Dosage

Figure 4.15. Settled Water Turbidity at 35 min. vs. Pressure Loss for 8.0 mg/L Dosage
performed at a 4 mg/L dosage, none of which were reproducible. The data collected for this series of experiments are presented in Table 4.6 and in Figures 4.16 - 4.19. Another indicator that the 5.0 mg/L dosage was the lowest possible is that the negative zeta potential values obtained in these experiments for the treated water were close to that of the raw water. With the zeta potential so close to that of the raw water, it is obvious that any lower dosage would probably not even be distinguishable from the raw water zeta potential.

A slightly increasing trend in the filtered and settled water turbidities can be seen as the headloss values are increased from one foot to 4 feet. However, as the headloss is increased further, a leveling off or decrease in turbidities can be seen. This suggests that the poorest mixing occurred at four feet of headloss. The zeta potential values show some fluctuations, but no consistent trends can be observed. Three experiments were performed at 4 feet of headloss to see if reproducibility could be established. Although there are some variations in the parameters, reasonable reproducibility was obtained. This degree of variations in the results was not unexpected because the coagulant dose was insufficient to destabilize all of the particles in the suspension.

20.0 mg/L Dosage with Good Chemical Conditions. The next set of experiments was designed to observe the effectiveness of static mixers using the sweep coagulation mechanism. The dosage was 20 mg/L with pH values ranging from 7.04 - 7.13 and headloss measurements from 0.25 - 8 feet. The data obtained are shown in Table 4.7 and Figures 4.20 - 4.23. As can be seen in Figure 4.21, actual charge reversal of the particles was observed at this dosage level indicating a small overdose of coagulant. However, other studies have
Table 4.6. Static Mixer Rapid Mixing Experiments, Alum Dosage = 5.0 mg/L

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Flow Rate (L/min)</th>
<th>Pressure Loss (inches of water)</th>
<th>pH</th>
<th>Average Filtered Water Turbidity (ntu)</th>
<th>Particle Count/mL</th>
<th>Zeta Potential (mV)</th>
<th>Settled Water Turbidity at 20 min. (ntu)</th>
<th>Settled Water Turbidity at 35 min. (ntu)</th>
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</thead>
<tbody>
<tr>
<td>H30</td>
<td>0.77</td>
<td>12.06</td>
<td>7.20</td>
<td>0.16</td>
<td>42000</td>
<td>-8.70</td>
<td>8.10</td>
<td>4.30</td>
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<tr>
<td>H29</td>
<td>1.08</td>
<td>23.79</td>
<td>7.27</td>
<td>0.23</td>
<td>37000</td>
<td>-11.40</td>
<td>7.80</td>
<td>4.70</td>
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<tr>
<td>H38</td>
<td>1.50</td>
<td>46.41</td>
<td>7.23</td>
<td>0.28</td>
<td>55000</td>
<td>-8.40</td>
<td>8.80</td>
<td>5.00</td>
</tr>
<tr>
<td>H25</td>
<td>1.54</td>
<td>48.48</td>
<td>7.28</td>
<td>0.40</td>
<td>64000</td>
<td>-10.80</td>
<td>10.40</td>
<td>7.60</td>
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<tr>
<td>H26</td>
<td>1.54</td>
<td>48.48</td>
<td>7.26</td>
<td>0.49</td>
<td>90000</td>
<td>-10.80</td>
<td>10.30</td>
<td>6.00</td>
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<td>H27</td>
<td>1.89</td>
<td>73.36</td>
<td>7.28</td>
<td>0.44</td>
<td>91000</td>
<td>-11.50</td>
<td>9.80</td>
<td>5.50</td>
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<td>H28</td>
<td>2.15</td>
<td>94.96</td>
<td>7.29</td>
<td>0.29</td>
<td>49000</td>
<td>-11.20</td>
<td>8.60</td>
<td>5.30</td>
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</table>
Figure 4.16. Average Filtered Water Turbidity vs. Pressure Loss for 5.0 mg/L Dosage

Figure 4.17. Zeta Potential vs. Pressure Loss for 5.0 mg/L Dosage
Figure 4.18. Settled Water Turbidity at 20 min. vs. Pressure Loss for 5.0 mg/L Dosage

Figure 4.19. Settled Water Turbidity at 35 min. vs. Pressure Loss for 5.0 mg/L Dosage
Table 4.7. Static Mixer Rapid Mixing Experiments, Alum Dosage = 20.0 mg/L with Good Chemical Conditions

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Flow Rate (L/min)</th>
<th>Pressure Loss (inches of water)</th>
<th>pH</th>
<th>Average Filtered Water Turbidity (ntu)</th>
<th>Particle Count/mL</th>
<th>Zeta Potential (mV)</th>
<th>Settled Water Turbidity at 20 min. (ntu)</th>
<th>Settled Water Turbidity at 35 min. (ntu)</th>
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</thead>
<tbody>
<tr>
<td>H43</td>
<td>0.41</td>
<td>3.37</td>
<td>7.06</td>
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<td>8.00</td>
<td>3.10</td>
<td>1.34</td>
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<tr>
<td>H31</td>
<td>0.79</td>
<td>12.82</td>
<td>7.04</td>
<td>0.04</td>
<td>N/A</td>
<td>9.10</td>
<td>1.90</td>
<td>1.00</td>
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<tr>
<td>H33</td>
<td>0.79</td>
<td>12.82</td>
<td>7.06</td>
<td>0.04</td>
<td>N/A</td>
<td>9.20</td>
<td>2.05</td>
<td>0.97</td>
</tr>
<tr>
<td>H35</td>
<td>1.10</td>
<td>24.95</td>
<td>7.09</td>
<td>0.04</td>
<td>N/A</td>
<td>9.40</td>
<td>2.10</td>
<td>0.95</td>
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<tr>
<td>H36</td>
<td>1.55</td>
<td>49.37</td>
<td>7.04</td>
<td>0.03</td>
<td>N/A</td>
<td>9.10</td>
<td>2.45</td>
<td>1.30</td>
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<tr>
<td>H39</td>
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<td>70.80</td>
<td>7.07</td>
<td>0.07</td>
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<td>8.40</td>
<td>2.50</td>
<td>1.18</td>
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<tr>
<td>H41</td>
<td>2.16</td>
<td>96.09</td>
<td>7.13</td>
<td>0.07</td>
<td>N/A</td>
<td>9.30</td>
<td>1.85</td>
<td>0.95</td>
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</tbody>
</table>
Figure 4.20. Average Filtered Water Turbidity vs. Pressure Loss for 20.0 mg/L Dosage with Good Chemical Conditions

Figure 4.21. Zeta Potential vs. Pressure Loss for 20.0 mg/L Dosage with Good Chemical Conditions
Figure 4.22. Settled Water Turbidity at 20 min. vs. Pressure Loss for 20.0 mg/L Dosage with Good Chemical Conditions

Figure 4.23. Settled Water Turbidity at 35 min. vs. Pressure Loss for 20.0 mg/L Dosage with Good Chemical Conditions
indicated that good coagulation occurs when zeta potential is within a range of +/- 10 mV. The chemical conditions are on the boundary between charge neutralization and sweep coagulation as seen in Figure 4.7. It is not totally clear whether the dominant mechanism is charge neutralization or sweep coagulation. All of the curves showed a flat response to variation of headloss and thus mixing intensity. This indicates that the static mixer is effective across the entire range of headloss values under what appears to be sweep coagulation conditions. When observing the settled water turbidity curves, it may be noticed that settled water quality did not reach that produced by the backmixed jar tests. When considering this, it should be kept in mind that only two stages of flocculation were used at G-values of 60 sec\(^{-1}\) and 40 sec\(^{-1}\). This is pointed out because these are not the ideal flocculation conditions for producing good settled water, such as the settled water in the initial jar tests; however, the filtered water quality was excellent. The two stage flocculation system simulated conditions for direct filtration.

**20.0 mg/L Dosage with Poor Chemical Conditions.** The final series of experiments was performed at a 20 mg/L dosage but in a pH range of 6.18 - 6.26 with headlosses ranging from 1 - 8 feet. This was done to observe the mixing effects under restabilization coagulation conditions. As seen in Figure 4.7, the operating point is near the boundary between restabilization and charge neutralization. The dominant mechanism, however, is definitely restabilization. Of all the experiments performed, the worst results were obtained under these conditions, once again demonstrating the strong influence of chemistry on coagulation. The data for these experiments can be seen in Table 4.8 and graphical representations of these data can be seen in Figures 4.24 - 4.27. The filtered water and settled water turbidity curves all
Table 4.8. Static Mixer Rapid Mixing Experiments, Alum Dosage = 20.0 mg/L with Poor Chemical Conditions

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Flow Rate (L/min)</th>
<th>Pressure Loss (inches of water)</th>
<th>pH</th>
<th>Average Filtered Water Turbidity (ntu)</th>
<th>Particle Count/mL</th>
<th>Zeta Potential (mV)</th>
<th>Settled Water Turbidity at 20 min. (ntu)</th>
<th>Settled Water Turbidity at 35 min. (ntu)</th>
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<td>H32</td>
<td>0.79</td>
<td>12.82</td>
<td>6.23</td>
<td>0.65</td>
<td>78000.00</td>
<td>9.60</td>
<td>12.70</td>
<td>10.70</td>
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<tr>
<td>H34</td>
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<td>24.95</td>
<td>6.18</td>
<td>0.67</td>
<td>85000.00</td>
<td>10.00</td>
<td>12.95</td>
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<td>H37</td>
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<td>49.37</td>
<td>6.15</td>
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<td>8.40</td>
<td>13.90</td>
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<td>70.78</td>
<td>6.26</td>
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<tr>
<td>H42</td>
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<td>96.09</td>
<td>6.20</td>
<td>0.79</td>
<td>110000.00</td>
<td>9.00</td>
<td>14.30</td>
<td>13.30</td>
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</table>
Figure 4.24. Average Filtered Water Turbidity vs. Pressure Loss for 20.0 mg/L Dosage with Poor Chemical Conditions

Figure 4.25. Zeta Potential vs. Pressure Loss for 20.0 mg/L Dosage with Poor Chemical Conditions
Figure 4.26. Settled Water Turbidity at 20 min. vs. Pressure Loss for 20.0 mg/L Dosage with Poor Chemical Conditions

Figure 4.27. Settled Water Turbidity at 35 min. vs. Pressure Loss for 20.0 mg/L Dosage with Poor Chemical Conditions
show a trend towards higher turbidities at higher headlosses. The lower pH of the water is probably interfering with the sweep coagulation mechanism and causing the restabilization of the particles. Also, the higher mixing intensities may be causing the particle enmeshments created under the sweep coagulation conditions to break up or even possibly never allowing them to form. The short detention times within the mixer at the higher flow rates and the characteristics of the precursors of aluminum hydroxide under these pH conditions are other possible reasons for the poor water quality. As stated in the "Coagulation" section of Chapter II, the Al(OH)$_3$ (s) takes between one and seven seconds to precipitate out and enmesh the colloids while mixing is occurring. Flow rates giving headloss values above 2 feet in the static mixer used for these experiments typically have detention times less than 0.8 seconds which is too short of a time interval for the sweep coagulation mechanism to take effect. Thus, if lower flow rates, longer detention times, and lower mixing intensities were used with this mechanism, better water quality may be attainable.

A combination of these influences working together is most likely the reason for the poor water quality in this series of experiments and also the reason for the trend towards higher turbidity values at higher mixing intensities with shorter detention times. It should also be noted that the zeta potential measurements obtained were very similar to those obtained under the 20 mg/L dosage with good chemical conditions, yet the final water quality was not even close to that achieved with good chemical conditions. This reinforces the earlier statement that there is a strong influence of solution chemistry in coagulation, especially the influence of pH.
The next step in the data analysis is to do some side by side comparisons of the various experimental results. This shows any general trends common to the data groups which may not be as obvious when looking at the graphs individually. Also, the filtered water and 35 minute settled water turbidities will be plotted versus G-value, energy dissipation, power per unit flow rate, and the Kolmogoroff microscale.

Figures 4.28 - 4.31 present the four main parameters versus pressure loss for all the experimental data groups. The most striking feature is the close match between the water quality data for the 12.5 mg/L dosage and the 20.0 mg/L dosage with good chemical conditions. This supports the earlier hypothesis that the 12.5 mg/L dosage would be just as good as the 20 mg/L dosage in treating the water using a direct filtration technique. It should also be noted in Figure 4.28 that both these lines show a fairly flat response, giving good filter effluent turbidities across the entire range of mixing intensities. In the case of the 8 mg/L dosage, it is noticed that there are more fluctuations in the filtered water effluent quality than there were in the 12.5 mg/L and 20 mg/L dosages. This is possibly because of the poor treatment conditions due to the inadequate dose of 8 mg/L.

The last two data groups are the 5 mg/L dosage and the 20 mg/L dosage with poor chemical conditions. Each of these experimental groups was considered to be at an inadequate treatment point on the alum coagulation diagram for the 13 ntu raw water. The main purpose in conducting these tests was to observe any sensitivity of treatment quality to mixing in the static mixer. For these chemical conditions, a slightly increasing trend in filtered
Figure 4.28. Comparison of Filtered Water Turbidities for Various Dosages
Figure 4.29. Comparison of Zeta Potential for Various Dosages
Figure 4.30. Comparison of 20 min. Settled Water Turbidity for Various Dosages
Figure 4.31. Comparison of 35 min. Settled Water Turbidity for Various Dosages
water effluent turbidity is noticed as headlosses are increased from 1 - 6 feet. Then, from 6 - 8 feet of headloss, the filtered water effluent turbidity begins to decrease again. It may be concluded that under poor chemical conditions, the least effective mixing takes place in the 2 - 6 feet of headloss range. Figures 4.30 and 4.31 showing the settled water turbidities also indicate the same general trends as the filtered water turbidity graph.

When analyzing the comparison of zeta potential results in Figure 4.29, it is interesting to note that the 12.5 mg/L dosage produced zeta potential values closest to zero which is probably why it was the most effective dosage among the charge neutralization experiments. Another interesting point is the almost identical lines for the two 20 mg/L dosages, one which gave such good treatment and the other which gave the worst treatment of all the experimental groups. The change in treatment quality is due to the pH difference between these experiments (6.2 vs. 7.1). At the lower pH of 6.2, there are enough H⁺ ions present to interfere with the hydrolysis speciation and the formation of AlOH₃ (s). This interference affects the coagulation mechanisms and does not allow good destabilization to occur. Overall, this result only serves to reinforce the point made earlier about the strong influence of chemistry in coagulation.

Figures 4.32 and 4.33 show the filtered water turbidity and 35 minute settled water turbidity versus G-value for all five experimental groups. These plots show the same trends as the previous set of figures (4.28 - 4.31). Under proper chemical conditions, the static mixer performed well over a range of G-values from approximately 500 - 8500 sec⁻¹. When the chemical conditions were inadequate, the G-value range of 3000 - 6000 gave the poorest quality treated water. It should be noted here that G-value was calculated from equation 2.3,
Figure 4.32. Comparison of Filtered Water Turbidities vs. G-Value

- 20.0 mg/L, pH = 6.2
- 5.0 mg/L, pH = 7.25
- 8.0 mg/L, pH = 7.2
- 12.5 mg/L, pH = 7.25
- 20.0 mg/L, pH = 7.05

Average Filtered Water Turbidity (ntu)

G-value (1/sec)
Figure 4.33. Comparison of 35 min. Settled Water Turbidity vs. G-Value
and the power input was calculated from equation 2.2. The volume considered in these G-value calculations was the section of pipe containing the static mixer blades, less the volume displacement of the mixer blades. These volumes were 18.03 ml (calculated) and 2.54 ml (measured), respectively, giving a net volume of 15.49 ml. The actual pipe diameter was 15/32 inches, and the length of pipe containing the mixer blades was 6-3/8 inches.

A comparison was also made between filtered water turbidities and 35 minute settled water turbidities versus energy dissipation per unit mass. These data can be seen in Figures 4.34 and 4.35. The energy dissipation rates covered a range from 4.1 - 591 ft-lbf/s/lbm (0.4 - 55 W/kg). The static mixer performed well across this entire range when good coagulation conditions were used. The mixer performed less effectively in the range of 100 - 300 ft-lbf/s/lbm under poor treatment conditions.

Figures 4.36 and 4.37 compare the filtered water turbidity and the 35 minute settled water turbidity to the power input per unit flow rate (hp/mgd). The same general trends seen in previous figures (4.32 - 4.35) are seen in these figures also. This parameter is included here because it provides an alternative way to compare various types of continuous flow rapid mixing processes. The calculation does not involve having to use the volume of the reactor, unlike the G-value and energy dissipation equations. The experiments covered the range of 0.06 - 1.7 hp/mgd and the results show adequate mixing across this entire range for good chemical conditions. Poor chemical conditions, however, showed a slight deficiency in mixing in the 0.5 - 1.1 hp/mgd range.

The water quality data was also plotted versus the Kolmogoroff microscale so that conclusions could be made in relation to some of the ideas that Amirtharajah and Trusler
Figure 4.34. Comparison of Filtered Water Turbidities vs. Energy Dissipation per Unit Mass
Figure 4.35. Comparison of 35 min. Settled Water Turbidity vs. Energy Dissipation per Unit Mass
Figure 4.36. Comparison of Filtered Water Turbidity vs. Power Input per Unit Flow Rate

- 20.0 mg/L, pH = 6.2
- 5.0 mg/L, pH = 7.25
- 12.5 mg/L, pH = 7.25
- 8.0 mg/L, pH = 7.2
- 20.0 mg/L, pH = 7.05
Figure 4.37. Comparison of 35 min. Settled Water Turbidity vs. Power Input per Unit Flow Rate
(1986) put forth in their paper dealing with the destabilization of particles by turbulent rapid mixing. This data can be seen in Figures 4.38 and 4.39. Amirtharajah and Trusler determined that minimum destabilization would occur when the Kolmogoroff microscale was 1.33 to 2.0 times the particles in the influent ($\eta \sim 1.33 \ d_i - 2.0 \ d_i$) for the viscous and inertial subranges. Based on their theory and an average particle size of 1 $\mu$m for these tests, it can be seen that all of the experiments conducted were operating well above the minimum destabilization point for both the viscous and inertial subranges. This corresponds with the good results obtained while operating under adequate chemical conditions at 12.5 mg/L and 20 mg/L.

**Comparison to Backmix Configuration and Empty Pipe Mixing**

**Backmix Comparison.** A comparison can be drawn between the direct filtration jar tests and the static mixing experiments at the 12.5 mg/L and 20 mg/L dosages, both at good chemical conditions (i.e. good pH values). Table 4.9 shows these data as well as the data for the empty pipe mixing experiments. The jar filtration tests using a backmix reactor produced filtered water turbidities of 0.12 ntu and 35 minute settled water turbidities of 1.43 ntu for the 12.5 mg/L dosage and the same flocculation conditions. The static mixer tests at the 12.5 mg/L dosage produced filtered water turbidities in the 0.07 - 0.10 ntu range and 35 minute settled water turbidities in the range of 1.0 - 2.1 ntu. Both of the jar test values fall within the experimental ranges of turbidities produced by the static mixer.

At the 20 mg/L dosage, the jar filtration tests produced a filtered water turbidity of 0.13 ntu and a 35 minute settled water turbidity of 0.80 ntu. The ranges for the 20 mg/L static mixer tests with good chemical conditions were 0.03 - 0.07 ntu and 0.95 - 1.34 ntu, respectively. The filtered water turbidities produced by the static mixer are slightly better,
Figure 4.38. Comparison of Filtered Water Turbidity vs. Kolmogoroff Microscale
Figure 4.39. Comparison of 35 min. Settled Water Turbidity vs. Kolmogoroff Microscale
Table 4.9. Comparison of Static Mixer to Backmix Configuration and Empty Pipe Mixing

<table>
<thead>
<tr>
<th>Mixer Type</th>
<th>Alum Dosage (mg/L)</th>
<th>pH</th>
<th>Settled Water Turbidity at 35 minutes (ntu)</th>
<th>Filtered Water Turbidity (ntu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Backmix</td>
<td>12.5</td>
<td>7.35</td>
<td>1.43</td>
<td>0.12</td>
</tr>
<tr>
<td>Static</td>
<td>12.5</td>
<td>7.15 - 7.30</td>
<td>1.0 - 2.1</td>
<td>0.07 - 0.10</td>
</tr>
<tr>
<td>Empty Pipe</td>
<td>12.5</td>
<td>7.20</td>
<td>1.65</td>
<td>0.11</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mixer Type</th>
<th>Alum Dosage (mg/L)</th>
<th>pH</th>
<th>Settled Water Turbidity at 35 minutes (ntu)</th>
<th>Filtered Water Turbidity (ntu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Backmix</td>
<td>20.0</td>
<td>7.30</td>
<td>0.80</td>
<td>0.13</td>
</tr>
<tr>
<td>Static</td>
<td>20.0</td>
<td>7.05 - 7.15</td>
<td>0.95 - 1.34</td>
<td>0.03 - 0.07</td>
</tr>
<tr>
<td>Empty Pipe</td>
<td>20.0</td>
<td>6.2</td>
<td>11.2</td>
<td>0.62</td>
</tr>
<tr>
<td>Static</td>
<td>20.0</td>
<td>6.15 - 6.25</td>
<td>10.4 - 13.3</td>
<td>0.65 - 0.80</td>
</tr>
</tbody>
</table>

while the settled water turbidities are not quite as good as the value from the jar filtration test. A possible reason for this is that the backmix configuration is more conducive to producing good settled water than the static mixer, while the static mixer holds the advantage for direct filtration.

**Empty Pipe Comparison.** An empty pipe mixing experiment at a 12.5 mg/L dosage with a pH of 7.2 produced a filtered water turbidity of 0.11 ntu and a 35 minute settled water turbidity of 1.65 ntu. The empty pipe experiments were conducted using exactly the same methods as those used in the static mixer experiments, the only difference being the lack of a mixer in the process flow. When compared to the ranges stated above for the static mixer
experiments at this dosage, it can be seen that the filtered water turbidity is almost within, but slightly above, the range produced by the static mixer. The settled water result is also within the range of that produced by the static mixer. However, it should be noted that most of the 35 minute settled water turbidities produced were less than approximately 1.4 ntu, which places the value for the empty pipe above the static mixer range.

Another empty pipe mixing experiment was conducted at a 20 mg/L dosage under poor chemical conditions (i.e. pH = 6.2). This experiment produced filtered and 35 minute settled water turbidities of 0.62 and 11.2 ntu respectively. The static mixer results were in the range 0.65 - 0.80 ntu for filtered water turbidity and 10.4 - 13.3 ntu for settled water turbidities. This is not a good comparison to make, however, because the extremely poor chemical conditions would tend to mask the effects of mixing.

Overall, the static mixer performed the same as or better than the backmix and empty pipe reactors under good chemical conditions. Under poor chemical conditions, the static mixer had about the same performance as an empty pipe. Both of these results strongly indicate the dominating influence that the proper chemical conditions have on coagulation.

Full Scale Plant Survey Results

A survey of 67 treatment plants in the United States was conducted, all of which were said to have static mixers as their rapid mixing process. This information was obtained from the AWWA database on surface water treatment plants from all over the United States. Of the 67 plant personnel to whom the questionnaire was mailed, 34 responses were received with 23 of those responses being useful. Responses which were not useful were typically either plants that did not actually have static mixers, or surveys in which the information
returned was unclear. Some of the data collected are displayed in Tables 4.10 and 4.11. Table 4.10 contains general plant information, such as flow rates, coagulants used, typical raw and finished water turbidities, and pH values. Also, the results of a yes or no type opinion question are displayed in Table 4.10. The opinion question was "Do you feel the static mixer does an adequate job?". Of the 23 useful responses, only three answered negatively to this question.

Table 4.10 also gives an estimation of what coagulation mechanism a plant is using for treatment based on pH and typical coagulant dosages. The coagulation mechanism was estimated using the alum coagulation diagram developed by Amirtharajah and Mills (1982) and the iron coagulation diagram developed by Johnson and Amirtharajah (1983). A layout of the full scale plant operating points where applicable on the alum coagulation diagram can be seen in Figure 4.40. It should be noted that the pH values given were not specified as to whether they were mixed or finished water. No clear trend towards use of static mixers for operation in the charge neutralization or sweep coagulation regimes can be seen in the survey information. Most of the plants (17 out of 23) use alum as a coagulant, but this probably is not specific to static mixers because alum is the most common coagulant used in water treatment.

Table 4.11 displays some of the important characteristics of the static mixers used by these various plants. The first interesting point is that 9 of the 23 plants use a Komax static mixer. It would not be prudent at this time, however, to state that the Komax mixer is the best choice for water treatment. The treatment approach employed by 19 of the 23 plants is a conventional type treatment scheme, the other 4 using direct filtration. This is significant
<table>
<thead>
<tr>
<th>Plant Name</th>
<th>Average Summer Flow (mgd)</th>
<th>Average Winter Flow (mgd)</th>
<th>Design Flow (mgd)</th>
<th>Coagulant Used</th>
<th>Average or Typical Coag. Dose (mg/L)</th>
<th>Typical pH</th>
<th>Possible Raw Water Coag. Mech.</th>
<th>Raw Water Turbidity (ntu)</th>
<th>Finished Water Turbidity (ntu)</th>
<th>Does Mixer Perform Adequately (Y/N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Denton WTP</td>
<td>20.00</td>
<td>10.00</td>
<td>30.00</td>
<td>ferric sulf.</td>
<td>15-144</td>
<td>8.30</td>
<td>S</td>
<td>9.00</td>
<td>0.08</td>
<td>Y</td>
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<tr>
<td>Grand Forks WTP</td>
<td>7.50</td>
<td>6.00</td>
<td>16.50</td>
<td>alum</td>
<td>20-100</td>
<td>6.75</td>
<td>S</td>
<td>56.00</td>
<td>0.15</td>
<td>Y</td>
</tr>
<tr>
<td>Pine Valley WTP</td>
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<td>25.00</td>
<td>56.00</td>
<td>alum</td>
<td>8.2</td>
<td>7.50</td>
<td>CN/S</td>
<td>0.72</td>
<td>0.04</td>
<td>Y</td>
</tr>
<tr>
<td>PUD #1 WTP</td>
<td>10.00</td>
<td>7.00</td>
<td>18.00</td>
<td>ACH</td>
<td>2.7</td>
<td>8.30</td>
<td>Unk.</td>
<td>0.30</td>
<td>0.06</td>
<td>Y</td>
</tr>
<tr>
<td>Appomattox River WTP</td>
<td>42.00</td>
<td>12.00</td>
<td>46.00</td>
<td>alum</td>
<td>29</td>
<td>7.00</td>
<td>S</td>
<td>20.00</td>
<td>0.15</td>
<td>Y</td>
</tr>
<tr>
<td>Cholla WTP</td>
<td>25.00</td>
<td>16.00</td>
<td>24.00</td>
<td>alum</td>
<td>10-20</td>
<td>7.80</td>
<td>CN/S</td>
<td>20.00</td>
<td>0.06</td>
<td>Y</td>
</tr>
<tr>
<td>Lake Gaillard WTP</td>
<td>45.00</td>
<td>28.00</td>
<td>80.00</td>
<td>alum</td>
<td>6.5-12</td>
<td>7.30</td>
<td>CN</td>
<td>0.90</td>
<td>0.04</td>
<td>N</td>
</tr>
<tr>
<td>Lake Gaillard WTP</td>
<td>45.00</td>
<td>28.00</td>
<td>80.00</td>
<td>alum</td>
<td>6.5-12</td>
<td>7.30</td>
<td>CN</td>
<td>0.90</td>
<td>0.04</td>
<td>N</td>
</tr>
<tr>
<td>Milton WFP</td>
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<td>3.70</td>
<td>6.00</td>
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<td>7.3</td>
<td>7.20</td>
<td>CN</td>
<td>7.40</td>
<td>0.03</td>
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<td>3</td>
<td>6.20</td>
<td>CN</td>
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<td>1.74</td>
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<td>CN</td>
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<td>Two Lick Creek WTP</td>
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<td>3.10</td>
<td>6.00</td>
<td>Ferric Chl.</td>
<td>8.2</td>
<td>9.00</td>
<td>S</td>
<td>2.90</td>
<td>0.05</td>
<td>Y</td>
</tr>
<tr>
<td>Ute Pass WTP</td>
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<td>0.50</td>
<td>1.00</td>
<td>Naolco 8157</td>
<td>20</td>
<td>8.30</td>
<td>CN/IB</td>
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<td>Y</td>
</tr>
<tr>
<td>Val Vista WTP</td>
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<td>100.00</td>
<td>140.00</td>
<td>alum</td>
<td>≥10</td>
<td>7.78</td>
<td>CN/S</td>
<td>7.08</td>
<td>0.08</td>
<td>Y</td>
</tr>
</tbody>
</table>

Note: CN = Charge Neutralization Coagulation, S = Sweep Coagulation, IB = Interparticle Bridging Coagulation, Unk. = Unknown
<table>
<thead>
<tr>
<th>Plant Name</th>
<th>Average Summer Flow (mgd)</th>
<th>Average Winter Flow (mgd)</th>
<th>Design Flow (mgd)</th>
<th>Coagulant Used</th>
<th>Average or Typical Coag. Dose (mg/L)</th>
<th>Typical pH</th>
<th>Possible Raw Water Coag.</th>
<th>Turbidity (ntu)</th>
<th>Finished Water Turbidity (ntu)</th>
<th>Does Mixer Perform Adequately (Y/N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Haverhill WTP</td>
<td>8.00</td>
<td>6.00</td>
<td>26.00</td>
<td>alum</td>
<td>20</td>
<td>7.50</td>
<td>S</td>
<td>1.00</td>
<td>0.05</td>
<td>Y</td>
</tr>
<tr>
<td>Perry WTP</td>
<td>40.00</td>
<td>25.00</td>
<td>45.00</td>
<td>alum</td>
<td>28</td>
<td>7.00</td>
<td>S</td>
<td>12.00</td>
<td>0.08</td>
<td>Y</td>
</tr>
<tr>
<td>St. Albans WTP</td>
<td>1.40</td>
<td>1.20</td>
<td>3.40</td>
<td>PAC</td>
<td>8-50</td>
<td>7.40</td>
<td>CN/S</td>
<td>8.00</td>
<td>0.10</td>
<td>Y</td>
</tr>
<tr>
<td>Charleroi WTP</td>
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<td>6.00</td>
<td>9.90</td>
<td>Stern-PAC</td>
<td>12-40</td>
<td>8.30</td>
<td>CN/S</td>
<td>5.00</td>
<td>0.04</td>
<td>Y</td>
</tr>
<tr>
<td>Citico Pump Station WTP</td>
<td>11.27</td>
<td>11.49</td>
<td>18.06</td>
<td>alum</td>
<td>14</td>
<td>7.20</td>
<td>CN</td>
<td>19.50</td>
<td>0.12</td>
<td>Y</td>
</tr>
<tr>
<td>Citico Pump Station WTP</td>
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<td>29.89</td>
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<td>CN</td>
<td>19.50</td>
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<td>Y</td>
</tr>
<tr>
<td>Santa Teresa WTP</td>
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<td>20.00</td>
<td>100.00</td>
<td>alum</td>
<td>20-40</td>
<td>7.30</td>
<td>S</td>
<td>6.40</td>
<td>0.03</td>
<td>N</td>
</tr>
<tr>
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<td>0.94</td>
<td>1.50</td>
<td>alum</td>
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<td>Unk.</td>
<td>10.00</td>
<td>0.09</td>
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<td>Y</td>
</tr>
<tr>
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<td>4.00</td>
<td>16.00</td>
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<td>7.70</td>
<td>CN/S</td>
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<td>4.00</td>
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<td>7.20</td>
<td>Unk.</td>
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<td>11.00</td>
<td>35.00</td>
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<td>22</td>
<td>7.20</td>
<td>S</td>
<td>0.70</td>
<td>0.25</td>
<td>N</td>
</tr>
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</table>

Note: CN = Charge Neutralization Coagulation, S = Sweep Coagulation, IB = Interparticle Bridging Coagulation, Unk. = Unknown
Figure 4.40. Full Scale Plant Operating Points on the Alum Coagulation Diagram
Table 4.11. Static Mixer Information from Plant Survey and Some Calculated Parameters

<table>
<thead>
<tr>
<th>Survey Data</th>
<th>Calculated Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant Name</td>
<td>Mixer Manufacturer</td>
</tr>
<tr>
<td>Denton WTP</td>
<td>Koch</td>
</tr>
<tr>
<td>Grand Forks WTP</td>
<td>Koch</td>
</tr>
<tr>
<td>Pine Valley WTP</td>
<td>Koch</td>
</tr>
<tr>
<td>PUD #1 WTP</td>
<td>Koch</td>
</tr>
<tr>
<td>Appomattox River WTP</td>
<td>Komax</td>
</tr>
<tr>
<td>Cholla WTP</td>
<td>Komax</td>
</tr>
<tr>
<td>Lake Gaillard WTP</td>
<td>Komax</td>
</tr>
<tr>
<td>Lake Gaillard WTP</td>
<td>Komax</td>
</tr>
<tr>
<td>Milton WFP</td>
<td>Komax</td>
</tr>
<tr>
<td>Philipsburg WTP</td>
<td>Komax</td>
</tr>
<tr>
<td>Riverside WTP</td>
<td>Komax</td>
</tr>
<tr>
<td>Two Lick Creek WTP</td>
<td>Komax</td>
</tr>
<tr>
<td>Ute Pass WTP</td>
<td>Komax</td>
</tr>
<tr>
<td>Val Vista WTP</td>
<td>Komax</td>
</tr>
</tbody>
</table>

Note: G value is calculated based on volume calculated from nominal pipe diameter and static mixer length given in survey.
No volume was subtracted for volume displacement of mixing elements.
Operating headloss, G Value, and energy dissipation calculations are based on average summer flow.

Note: C = Conventional, D = Direct Filtration, N/G = not given in survey, N/A = not applicable because of missing survey information.
Table 4.11 (continued). Static Mixer Information from Plant Survey and Some Calculated Parameters

<table>
<thead>
<tr>
<th>Plant Name</th>
<th>Manufacturer</th>
<th>Average Flow (mgd)</th>
<th>Treatment Scheme</th>
<th>Average Summer Flow (mgd)</th>
<th>Mixer Number</th>
<th>Number of Elements</th>
<th>Pipe Dia. (in)</th>
<th>Operating Headloss Across Mixer (ft)</th>
<th>Length/Diameter Ratio (L/D)</th>
<th>G Value (1/sec)</th>
<th>Energy Dissipation per Unit Mass Flow Rate (ft-lbf/s/lbm)</th>
<th>Power per Unit Mass Flow Rate (hp/mgd)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Haverhill WTP</td>
<td>Kenics</td>
<td>8.00</td>
<td>C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>N/G</td>
<td></td>
<td>4.17</td>
<td>N/A</td>
<td>N/A</td>
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<tr>
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<td>C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>N/G</td>
<td></td>
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<tr>
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<td>C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>N/G</td>
<td></td>
<td>6.00</td>
<td>N/A</td>
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<td>4</td>
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<td>N/G</td>
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</tbody>
</table>

Note: G value is calculated based on volume calculated from nominal pipe diameter and static mixer length given in survey.
No volume was subtracted for volume displacement of mixing elements.
Operating headloss, G Value, and energy dissipation calculations are based on average summer flow.

Note: C = Conventional, D = Direct Filtration, N/G = not given in survey, N/A = not applicable because of missing survey information.
because it is commonly thought that static mixers are best employed when fast intense mixing is required. This type of mixing is normally associated with direct filtration treatment plants, but in the survey results it is seen that the static mixer is effective in both conventional and direct filtration applications. The detention times within the static mixers range from 0.1 - 6.3 seconds, with values at a variety of points within this range.

The physical characteristics of the static mixers are the next parameters to be considered. The number of mixing elements used ranges from 1 - 4, and no clear trends towards a certain number of elements for a given manufacturer can be seen. Pipe diameters range from 108 inches at the largest to 6 inches at the smallest, with many different sizes in between. Pipe size is typically determined by flow and headloss requirements and there should be no relation between mixing effectiveness and pipe diameter, other than the influence of these parameters. The $L_{SM}/D$ ratio is a commonly used design parameter for static mixers. This ratio was calculated when possible, and it was found that values ranged from approximately 1 - 6. From the literature presented in Chapter II, in the turbulent mixing section, $L_{SM}/D$ ratios of 3 - 9 were typically recommended as providing good mixing. Of the plants surveyed, 18 out of 23 had $L_{SM}/D$ ratios within this range.

The final group of characteristics to be considered are the calculated design parameters most often used by process designers when considering a static mixer for use in the water treatment industry. The operating headloss across the static mixer is an important design consideration. It should be selected so that at higher flows it will not be too excessive, while at lower flows it should still provide adequate mixing. The survey indicates that most plants with static mixers operate at pressure losses of approximately 0.5 - 6 feet of water.
These headloss values are somewhat higher than the ones recommended by Kawamura (1991), who suggests a maximum headloss of 2 feet across the static mixer. Only 5 of the 23 plants have typical operating headloss values below 2 feet.

G-values were calculated based on the volume of the static mixer, the average summer flow rate, and the headloss across the mixer at this flow rate. G-values ranged from 461 - 10,500 sec⁻¹. However, most of the G-values were within the range of 1,000 - 4,000 sec⁻¹. These are fairly normal G-value ranges, although it has been suggested by Amirtharajah and Trusler (1986) that the average G-value range of 1,500 - 3,500 sec⁻¹ is to be avoided for 3 µm particles in a backmix type reactor. Another possible parameter to be used in comparisons between different types of rapid mixers is the GT value, because it takes into consideration the amount of time that the water is agitated in mixing.

Energy dissipation per unit mass calculations were also performed although this is not a commonly used design parameter in water treatment. An operating range of 2.25 - 1170 ft-lb/s/lbm (0.2 - 108.5 W/kg) was found for these calculations, but most of the plants were within the range of 12 - 67 ft-lb/s/lbm (1 - 6.5 W/kg).

Finally, the power input per unit flow rate (hp/mgd) was calculated for these plants to get an idea of what range a typical plant might operate in when using a static mixer and for use in comparison of the static mixer to other types of full scale rapid mixing processes. The plants operated throughout the range of 0.0 - 2.26 hp/mgd, but most fell within the range 0.07 - 1.05 hp/mgd which corresponds reasonably well with the experimental results. Cleasby et al. (1989) reported on the overall operating range of several different types of rapid mix units (backmix, in-line blender, jet injection, hydraulic, and static) using this parameter for
comparison. Cleasby et al. (1989) found that all of these different types of mixers operated in the range of 0.11 - 1.50 hp/mgd with a median value of 0.32 hp/mgd. As seen in Table 4.11, the static mixers surveyed are almost all within this range with a median value of 0.51. This indicates that static mixers perform on a comparative level with other types of rapid mixing processes if the right parameter is used to relate them to one another. This also shows that static mixers can operate across an entire range just as well as other types of mixers. For future studies involving multiple types of mixers, the use of this parameter is strongly suggested.

Comparison of Plant Survey Results with Static Mixer Experiments

Several comparisons can be made between the experimental results and the plant scale static mixer survey results. Most of these comparisons, however, involve the calculated parameters rather than the general physical characteristics. This is because of the small scale at which the coagulation experiments were conducted. For example, the $L_{SM}/D$ ratio for the experimental static mixer was 13.6, which is well above the typical $L_{SM}/D$ ratios found in the survey. This disproportionate ratio was needed so that enough headloss could be generated at the small scale and low flow rates used in the experiment. In addition to this consideration, it can be easily seen that the rest of the physical characteristics such as number of mixing elements, pipe diameter and pipe length will also be different.

In contrast to the physical characteristics, the operating characteristics of the experimental static mixer were more easily compared to the survey results. The static mixers were tested over a headloss range of 0.25 - 8.5 feet of water pressure head. This range corresponds very well with the typical operating headloss values of 0.5 - 6 feet of water for
the full scale plant data. As stated in the opinion question posed in the static mixer survey, most of the plant operators felt that the static mixer did an adequate job of mixing. These positive responses came from plants operating at a variety of headloss values. These opinions are confirmed by the static mixer experimental results which show that with the proper chemical conditions for coagulation static mixers perform well over the entire range of headlosses at which they were tested. Detention times within the experimental static mixer ranged from approximately 0.5 seconds to 2.5 seconds. Detention times within the plant static mixers covered an even broader range, from 0.1 - 6.3 seconds.

Also, several of the plants operate in the charge neutralization regime while others operate in the sweep coagulation regime, yet all of them have good mixing and good treated water quality. This indicates that the static mixer can be effective in both the sweep coagulation and charge neutralization regimes. This statement is justified in the experimental results because of the good treatment obtained at the 12.5 mg/L dosage and the 20 mg/L dosage with good chemical conditions. These two dosages represent charge neutralization coagulation and sweep coagulation, respectively.

The G-value range of the experimental data also corresponded very well with the full scale plant data. Experimental G-values ranged from 500 - 8500 sec\(^{-1}\) while full scale plant G-values ranged from 460 - 10,500 sec\(^{-1}\) with most falling in the 1,000 - 4,000 sec\(^{-1}\) range. The static mixer experiments show that good mixing performance is achieved across the entire range of G-values under good chemical conditions as seen in Figures 4.32 and 4.33. The energy dissipation per unit mass can also be compared. Most of the plant data fell within the 12 - 67 ft-lbf/s/lbm (1 - 6.5 W/kg) range of energy dissipation per unit mass. The
experimental results in Figures 4.34 and 4.35 show good mixing for the entire range of 0 - 600 ft-lbf/s/lbm (0 - 55 W/kg) and excellent results in the 12 - 67 ft-lbf/s/lbm (1 - 6.5 W/kg) range. For the power input per unit flow rate data, the experiments showed good results across the entire range of 0.05 - 1.7 hp/mgd, and excellent results in the 0.07 - 1.05 range which is where most of the plants were operating.
CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Conclusions on Static Mixer Effectiveness

Overall, the static mixer can be very effective in surface water treatment processes. This statement is based on both the experimental results as well as the full scale plant survey information. Because of its low operations and maintenance costs, the static mixer is an attractive alternative to other mixing configurations such as the backmix reactor. Based on the experimental results and the full scale plant survey, several conclusions can be reached on the design of static mixers in water treatment. Static mixers may be used in either conventional or direct filtration treatment trains. They may also be used for either charge neutralization or sweep coagulation mechanisms. It should be noted however, that typically less intense, slower mixing is desired in sweep coagulation because of the longer chemical reaction times while fast, intense mixing is desired for charge neutralization because of the relatively short chemical reaction times.

Static mixers perform well over an entire range of headlosses as can be seen in both the experimental results as well as the survey results. Experimental results show good mixer performance over a headloss range of 0.5 - 8.5 feet of water while plants typically operated with headlosses from 0.5 - 6 feet of water. There is also a wide range of G-values which are
acceptable. Experimental G-values ranged from 500 - 8500 sec\(^{-1}\) and most of the full scale plant G-values ranged from 1000 - 4000 sec\(^{-1}\). A third parameter which can be used is the energy dissipation per unit mass. Most of the full scale plants were in the 12 - 67 ft-lbf/s/lbm (1 - 6.5 W/kg) range for this parameter, but the experiments indicate good results from 0 - 600 ft-lbf/s/lbm (0 - 55 W/kg). An excellent parameter to use when comparing mixers is the power input per unit flow rate (hp/mgd). Almost all of the plants were found to operate in the range of 0.07 - 1.05 hp/mgd for this parameter. This corresponds well with the range 0.11 - 1.50 hp/mgd, which comes from the data presented by Cleasby et al. (1989) on various types of mixers. The experiments also showed adequate mixing occurring in the 0.05 - 1.7 hp/mgd range.

The number of mixing elements normally used in the full scale plants was anywhere from 1 - 4 depending on flow rate and headloss characteristics through the mixer. The most common number of elements seen in the full scale plant survey were 2 and 3. Pipe diameter and mixer length are functions of flow rate, headloss, and number of mixing elements and should be determined based on these parameters. Adequate detention times in the experimental mixer ranged from 0.4 - 2.0 seconds while detention times in the full scale plant mixers ranged from 0.1 - 6.3 seconds. Based on information from the literature review, the introduction of the coagulant or any other chemicals to the process flow stream should be in the center of the pipe just before the static mixer.

An additional conclusion that can be drawn from this study is that chemistry has a greater influence on treated water quality than mixing. When compared to the effects of chemistry (i.e. good chemical conditions versus bad chemical conditions), the differences in
treatment quality with variations in mixer performance and design are usually small. This is illustrated well by the two series of experiments using a 20 mg/L dosage and pH values of 6.2 and 7.1. The dosages were identical but the treatment quality was completely different due to the variation in pH.

**Design Recommendations**

The following are recommendations for the design parameters to be used when designing a static mixer for the rapid mix process in surface water treatment. These recommendations are based on experimental results, full scale plant survey information, and information in the current literature.

- Static mixers may be used in either conventional or direct filtration water treatment applications with either sweep or charge neutralization coagulation.

- A recommended headloss range for design is from 1 - 6 feet of water pressure head, with the normal average day operating headloss being in the 2 - 3 foot range.

- The G-value range should be from 1,000 to 4,000 sec⁻¹, while normal operating conditions give a G-value of 1,500 - 2,500 sec⁻¹.

- The maximum operating range for the energy dissipation per unit mass is 10 - 160 ft-lbf/s/lbm (1 - 15 W/kg), with normal operating characteristics in the 20 - 55 ft-lbf/s/lbm (2 - 5 W/kg) range.

- The power input per unit flow rate is a good parameter for design and should range from 0.05 - 1.05 hp/mgd, with normal operating conditions in the 0.20 - 0.70 hp/mgd range.
The number of mixing elements to be used should be between 2 and 4 elements.

The detention time in the static mixer should be kept below 2 seconds for the charge neutralization mechanism and between 1 and 6 seconds for the sweep coagulation mechanism.

The chemicals to be mixed should be introduced in the center of the pipe just before the static mixer.

Recommendations for Further Research

Further investigation of the effectiveness of static mixers in water treatment should be undertaken. A study is needed on side by side comparisons of different types of static mixers to determine which mixing elements work best for coagulation. At the same time, the minimum number of elements required for good mixing could also be determined for the various types of static mixers. A detailed study comparing the various types of rapid mixing units with static mixers would also be helpful to design engineers trying to select the best one for their particular application.

Also, experiments should be done on several different scales using the same type of static mixer under the same conditions. This would provide a meaningful look at scale up effects when extrapolating from bench scale studies to the full scale treatment plant. The use of a pilot plant type configuration would be helpful in the study of scale up. Finally, it would be useful to investigate the size of the mixing eddies within the static mixer along with various particle sizes to see how they correspond with Amirtharajah and Trusler's theory (1986). This might be helpful in pinpointing the best G-value range for the static mixer.
APPENDIX A

STATIC MIXER SURVEY FORM
BRAND X Water Treatment Plant

A. General Information

1. What overall treatment scheme is used? (Conventional, Direct Filtration, or In-Line Filtration)

2. Is there more than one treatment train? Y / N If so, how many? ____

3. Is the In-Line Static Mixer the only rapid mixing process used for all treatment trains? Y / N

3a. If no, what others are used? (Basin Mech., In-Line Mech., In-Line Hydraulic)

3b. Are these used in series or parallel with the Static Mixer? S / P

4. Do you feel the Static Mixer does an adequate mixing job? Y / N

4a. If no, please give comments on how it is inadequate. ______________________________

B. Plant Capabilities

1. Does flow vary greatly during a given season? Y / N If so, please give range.

2. Average plant flow rate: Summer _________ (mgd) Winter _________ (mgd)

3. Peak flow rate: _________ (mgd)

4. Design flow rate: _________ (mgd)

C. Water Quality and Treatment Parameters

1. Does raw water quality vary greatly over a given day? Y / N

2. Water Quality Parameters:

<table>
<thead>
<tr>
<th>Raw Water Parameters</th>
<th>Finished Water Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
</tr>
<tr>
<td>Turbidity (NTU):</td>
<td></td>
</tr>
<tr>
<td>pH:</td>
<td></td>
</tr>
<tr>
<td>Color (CU):</td>
<td></td>
</tr>
<tr>
<td>Alkalinity (mg/L):</td>
<td></td>
</tr>
<tr>
<td>TOC (mg/L):</td>
<td></td>
</tr>
<tr>
<td>Temperature:</td>
<td></td>
</tr>
<tr>
<td>Hardness (mg/L; as CaCO₃):</td>
<td></td>
</tr>
</tbody>
</table>
3. Chemicals added upstream of Static Mixer:

<table>
<thead>
<tr>
<th>Chemical</th>
<th>Dose (include units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coagulant:</td>
<td></td>
</tr>
<tr>
<td>Polymer:</td>
<td></td>
</tr>
<tr>
<td>pH Adjustment:</td>
<td></td>
</tr>
<tr>
<td>Disinfectants:</td>
<td></td>
</tr>
<tr>
<td>Oxidants:</td>
<td></td>
</tr>
<tr>
<td>Clays:</td>
<td></td>
</tr>
<tr>
<td>Other Chemicals:</td>
<td></td>
</tr>
</tbody>
</table>

D. Static Mixer Parameters

1. Mixer manufacturer: ____________________________

   Model name: _______________  Model number: ____________________________

2. Length of mixer: _________ (ft.)

3. Number of mixing elements inside mixer: __________

4. Pipe diameter: __________ (in.)

5. Headloss across mixer at a given flow rate:

   Headloss: __________ ( )  Please indicate units for headloss
   Flow: __________ (mgd)

E. Additional Comments: ____________________________________________

________________________________________________________________________

________________________________________________________________________

F. Consent to Publish Data

1. May we publish this data along with plant identification? Y / N

2. May we publish this data without plant identification (ie: Plant X)? Y / N

3. Would you like a copy of any publication that results from this research? Y / N

Name (Print): __________________________________________ Title: __________________________

Signature: __________________________________________  Date: __________________________

Name of person to contact if additional information is needed: __________________________
(If different than above) Phone number of contact: __________________________
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