  Journal of Water Supply: Research and Technology—AQUA | 49.6 | 2000

Initial (flash) mixing by water jet diffusion

Susumu Kawamura

ABSTRACT

The process of coagulation is one of the most important unit processes for nearly all water treatment plants. An integral part of coagulation is flash mixing (initial mixing). Chemical pretreatment using coagulant is the standard unit process in the field of water treatment and is considered to be a part of the process for tertiary filtration of secondary effluent and the combined sewer overflow. Industrial wastes also often require coagulants to achieve treatment goals.

The purpose of flash mixing is to quickly and uniformly disperse coagulant throughout the process water. Dispersion time is ideally less than 1 s for metallic coagulants such as alum and ferric salts. The jet diffusion type flash mixing system achieves this difficult task using up to 25–30% less coagulant, and significantly reduces sludge production.

Key words | coagulation, design, dispersion, flocculation, mixing, saving

Susumu Kawamura
Montgomery Watson Americas, Inc.
300 North Lake Avenue, Suite 1200
Pasadena, CA 91101
USA
E-mail: *susumu.kawamura@us.mw.com*

INTRODUCTION

All water treatment plants utilizing chemical coagulants to destabilize suspended solids in raw water should disperse the coagulant quickly and uniformly throughout the process water. This unit process is called coagulation and can only be properly achieved through the use of a good flash mixer.

The importance of a flash mixer, often called an initial mixer, has been emphasized by many authors (Stumm and O'Meria 1968; ASCE *et al.* 1969; Weber 1972; Kawamura 1973, 1976, 1991, 1996; Amirtharaja 1979; Montgomery Consulting Engineers 1985; Lang and Kawamura 1988; AWWA 1991). A good flash mixer should incorporate several important features: it should be simple, reliable, and cost-effective, have minimum headloss, operate quietly, and have low operations and maintenance costs.

Many design engineers are unaware that the volume ratio of coagulant and process water is usually in the range of one part to 50,000 parts: far beyond the ordinary liquid-to-liquid mixing ratios of most industries. Consequently, flash mixers designed by these individuals are not used by plant operators because of their ineffectiveness.

The pump diffusion flash mixing system, operating in more than 40 actual installations in the United States and Australia, possesses the necessary features of a good flash mixer. The design has also been modified, correcting earlier problems, since it was first created by the author in the early 1970s.

This paper presents some special design issues and design guides/criteria, both historical and current, for the initial mixer (flash mixer). There is also a brief discussion of the flash mixing system designed and installed at the Henry Mills Filtration Plant of the Metropolitan Water District (MWD) of Southern California and the Prospect Water Filtration Plant in Sydney, Australia.

HISTORICAL REVIEW OF FLASH MIXING

The first detailed design guides on flash mixing are found in the *ASCE Manual of Engineering Practice*, Number 19 (ASCE 1940). It describes two classes of initial mixing methods. The first uses the kinetic energy of the main body of raw water flowing through the plant and includes the baffled chamber or channel, hydraulic jump channel and tangential or spiral flow tanks. The second class utilizes an external source of energy for mixing and includes chambers with mechanical mixers and air agitation. A design guide published in the manual indicates that headloss should be between 1 and 3 feet (0.3–1 m) for the first class. The power equivalent of this headloss, based on a 75% overall pumping efficiency, is 0.23–0.70 hp per mgd of flow (0.05–0.14 kW ML^{-1}). The manual also states that a power of 0.25 hp per mgd (0.05 kW ML^{-1}) is required for rapid mixing by means of a mechanical mixer, based on the average horsepower of installed mechanical flash mixers. The power requirements for air mixing are said to range from 1 to 5 hp per mgd of flow (0.2–1 kW ML^{-1}).

In 1969 the American Society of Civil Engineers (ASCE), together with the American Water Works Association (AWWA) and Conference of State Sanitary Engineers (CSSE), published a revised version of the water treatment design book (ASCE/CSSE/AWWA 1969). The design guides were not much different from the old version except the recommended power requirement for flash mixing was changed to 0.25–1 hp per mgd (0.05–0.2 kW ML^{-1}) of plant flow.

More recent design manuals (ASCE/AWWA 1997) released by the AWWA and ASCE, suggest using the product of velocity gradients (G in s^{-1}), mixing time (t in s) as design guides: G × t. The suggested range for G is 600–1,000 s^{-1} and a range of 1,000–2,000 for G × t.

The Department of Health Services or equivalent state regulatory agency publishes recommended design criteria for major water treatment unit processes, including flash mixing of coagulants, based primarily on the Ten States Design Criteria (Great Lakes: Upper Mississippi River Board of State Sanitary Engineers 1992). Although the regulatory agencies insist on a minimum flash mixing time of 30 s, this does not meet the needs of the adsorption–destabilization concept, mainly because of the back-mixing phenomenon: adsorption of added coagulant on pre-formed flocs instead of suspended solids in the raw water.

Currently, the most widely accepted design criterion for designing a flash mixing system is instantaneous mixing of coagulant with a G × t ranging from 300 to 2,500 (1,000 average); this does not exhibit any significant back-mixing effect. The types of mixing system which satisfy this guideline are diffusion mixing by pressured water jets, mechanical mixers, and in-line static mixers. Among them, preference is given to diffusion by pressured water jets because:

1. there is essentially no additional headloss by the mixing;
2. the degree of mixing can be controlled by adjusting jet velocity;
3. the power consumption is approximately 20% of a mechanical mixing system;
4. it is proven to be effective;
5. it requires minimum operation and maintenance; and
6. it has a low capital requirement.

Design criteria and design guides for water jet diffusion may be found in recent publications such as that by the author (Kawamura 1991).

Table 1 presents examples of mechanical flash mixers installed at various plants. Note that the average horsepower (hp) per mgd for the mechanical flash mixer is 0.85 (0.17 kW ML^{-1}). This is at the upper end of the range recommended by the revised ASCE manual: 0.25–1.0 hp per mgd (0.05–0.02 kW ML^{-1}).

Table 2 lists several installations of pump diffusion flash mixing systems. The average horsepower of the pumps is 0.16 per mgd (0.03 kW ML^{-1}), which is approximately 20% of the power requirement of mechanical mixer systems.

Properly designed in-line static mixers are also effective in satisfying the aforementioned design guideline. However, under a minimum plant flow rate, the mixing energy drops dramatically. There is also the potential problem of debris, fish and scale formation clogging the blender. Moreover, the required loss of head across the blender under the plant's design flow rate is 2–4 feet (0.6–1.2 m) which is rather high.

BASIC CONSIDERATIONS

Fine suspensions in raw water (including bacteria and viruses) are removed through the use of coagulant, which destabilizes the electrical charge of the suspensions allowing them to enmesh into metal hydroxide (floc); the floc is

 Journal of Water Supply: Research and Technology—AQUA | 49.6 | 2000

Table 1 | Typical mechanical flash mixer installations

Plant	Flow rate (mgd)	Mechanical mixer installed: No. of units	hp of each	Total hp	hp per mgd
Behner WTP Pasadena, CA	7.5	1	10	10	0.75
Davenport WTP Davenport, IA	15	2	7.5	15	1.00
Badger WTP San Diguito, CA	27	2	10	20	0.74
Stanton WTP Stanton, DE	30	4	20	80	2.67
Larton WTP Fairfax, VA	40	2	25	50	1.25
Helix WTP Helix, CA	67	1	50	50	0.75
Jersey WTP Jersey City, NJ	80	3	15	45	0.56
Bridgeport WTP Bridgeport, CT	100	6	7.5	45	0.45
La Mesa WTP Manila, Philippines	200	3	40	120	0.33
Foothill WTP Denver, CO	250	4	5	20	0.08
Aqueduct WFP Los Angeles, CA	600	8	100	800	1.33
Guarau WTP San Paulo, Brazil	750	2	150	300	0.33
				Average	0.85

Table 2 | Typical diffusion mixing by pressured water

Plant	Flow rate (mgd)	Pump installed: Number	hp of motor	Total hp	hp per mgd
Royer Nesbit WTP Cucamonga, CA	4.5	1	1	1	0.22
Waterman WTP Fairfield, CA	15	1	3	3	0.20
Southeast WTP Salt Lake City, UT	20	1	3	3	0.15
UTE WTP Grand Junction, CO	35	1	3	3	0.09
Wemlinger WTP Aurora, CO	40	1	5	5	0.13
Otay WTP San Diego, CA	40	1	5	5	0.13
Bollman WTP Contra Costa, CA	80	1	10	10	0.13
Anstay Hill WW Adelaide, Australia	85	1	10	10	0.12
Santa Teresa WTP Santa Clara, CA	100	2	7.5	15	0.15
Val Vista WTP Phoenix, AZ	140	1	15	15	0.11
Jordan Valley WTP Salt Lake City, UT	190	1	30	30	0.16
Henry Mills WFP MWD of So.CA	330 One is standby	3	50	100	0.30
				Average	0.16

then removed by clarification followed by the filtration process.

Floc is generally formed in two stages: coagulation and flocculation. Coagulation—the destabilization of charge on colloids and fine suspended solids measuring less than several micrometers in size by coagulant, including inorganic coagulants or cationic polymers—is most effectively achieved by polyvalent ions produced by certain coagulants. This is based on the Schulze-Hardy rule, which states, the higher the valence, the greater the coagulative power (Stumm and O'Meria 1968; ASCE/CSSE/AWWA 1969; Weber 1972; Kawamura 1973): $3^+ > 2^+ > 1^+$ (approximately 1,000:30:1 ratio).

This coagulation process occurs instantaneously when metal coagulant is fed to raw water; hydrolytic reactions of the metal coagulants occur in a fraction of a second and produce hydroxo-compounds (floc) under the proper pH conditions (5.5–7.5).

Flocculation follows the rapid dispersion of coagulant by the flash mixing system. This gentle mixing phase accelerates the rate of particle collisions causing the agglomeration of electrolytically destabilized colloidal particles into settleable and filterable size particles.

Flash mixing, an integral part of the coagulation process, quickly and uniformly disperses coagulant throughout the raw water. Effective flash mixing is particularly important when using metal coagulants such as alum and ferric coagulants since they are hydrolysed within a fraction of a second and subsequent adsorption to colloidal particles is almost immediate. However, in practical design, the dispersion of metal coagulants should be completed within 1–2 s. The time requirement for other water treatment chemicals such as polyelectrolytes is not as critical since they do not undergo hydrolytic reactions.

There are many important considerations (Hardy 1900; Olin and Gauler 1938; Sayer 1960; Black 1960) for the selection and design of an effective flash mixing system:

1. type of coagulant;
2. size and shape of the pipe or channel where flash mixing is applied;
3. number and characteristic of each chemical fed at the flash mixer;
4. available headloss for flash mixing;
5. variations in plant flow rate;
6. capital and operations and maintenance costs;
7. coagulant feed point in relation to the flash mixer;
8. magnitude of mixing energy and dispersion time;
9. location of flash mixer in relation to subsequent processes; and
10. other miscellaneous items for site specific conditions.

Optimum coagulation is dependent on four conditions: (1) pH of the process water; (2) duration of coagulant dispersion; (3) no other chemical which directly reacts with the coagulant is fed at the same time as the coagulant; and (4) proper coagulant dosage.

The pH of the raw water is very important because the coagulation process requires an adequate amount of trivalent or higher ionic species to effectively reduce the electrical charge of the colloidal suspensions. As illustrated in Figure 1 (Stumm and O'Meria 1968), the lower the pH, the better the production of the species. This also explains why acidification of high pH raw water prior to the addition of alum often improves coagulation with reduced alum dosage, especially in the case of the enhanced coagulation process.

There are a number of actual water treatment plants which simultaneously feed several chemicals into the flash mixer together with alum. This design is not recommended since it often lowers the effectiveness of the alum coagulation process. For example, when anionic polymer, lime, activated carbon and chlorine are fed at the same point as alum, the anionic polymer directly reacts with the alum. Lime then raises the pH above 8, thereby minimizing the production of multivalent species in addition to producing a high level of dissolved aluminium in the flocculating water instead of forming aluminium hydroxide. The activated carbon and chlorine react with each other and the effectiveness of both chemicals is lost. Alum floc may begin to adsorb on to the carbon further reducing the proper functioning of both chemicals. One exception is to feed both alum and cationic polymers together, even mixing them just before flash mixing; several plants currently utilize this practice without any problems.

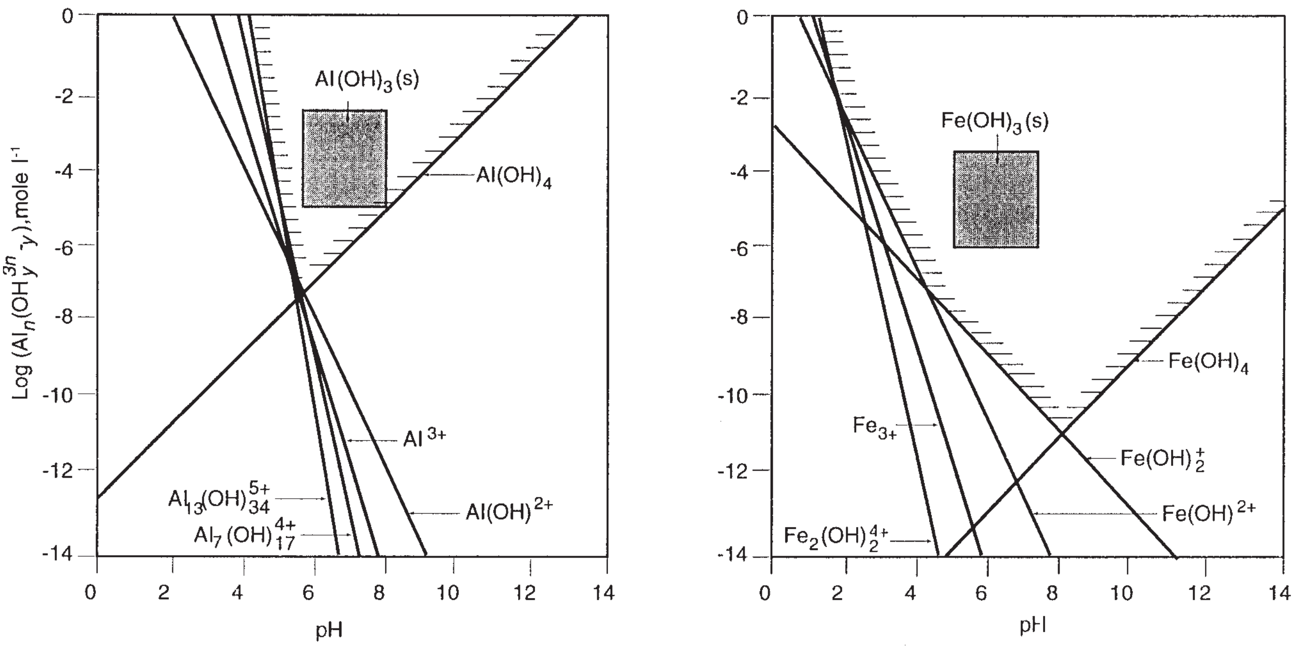


Figure 1 | Solubility of alum and ferric flocs versus pH.

SPECIAL DESIGN ISSUES

The design of all flash mixing systems, including diffusion mixing by pressured water jets, is generally based on the design flow rate of the plant. However, a treatment plant rarely operates at the designed flow rate all the time. An average daily flow rate is ordinarily about 65% of the design flow rate and as low as 25% during months of cold weather. In general, the plant may operate at the maximum daily flow rate (designed flow rate) only 2–4 weeks yr^{-1}.

Current practice in designing a flash mixing system is based on the plant designed flow rate (Kawamura 1991; AWWA 1991; ASCE/AWWA 1997). However, one consideration that is often overlooked is the adjustment of hydraulic conditions during low plant flow rates. In some treatment plants, when the plant flow rate is much lower than the designed flow rate, plant operators have found the flash mixing system to be completely ineffective or the required dosage of alum or ferric coagulant is higher than indicated by jar test and pilot test. Visual observation of several plants has shown an unusually high accumulation of floc inside the pipe located downstream of the mixer. This signifies that uniform dispersion of alum does not occur during periods of low plant flow. For example, one treatment plant continually operates at less than 20% of its designed flow rate because actual community demand is much lower than originally anticipated. This plant requires a much higher alum dosage than suggested by jar tests and also exhibits heavy accumulation of alum sludge on the wall of the pipe located just downstream of the jet mixing flash mixer.

A common cause of these flash mixing problems is the location of the coagulant application points in relation to the mixing system. Coagulant must be fed at the mixing device in order to obtain effective coagulation. This is absolutely essential when utilizing any metal coagulant as they undergo hydrolytic reactions with a fraction of a second. Quite often, the coagulant is fed some distance upstream of the mixing device. The worst case scenario involves dropping coagulant on to the surface of the water from a chemical feed pipe.

Another common factor contributing to flash mixing problems is the high dilution of metal coagulants such as

Journal of Water Supply: Research and Technology—AQUA | 49.6 | 2000

liquid alum and ferric coagulant with utility water before being fed to the raw water. Although it appears that dilution makes sense—better dispersion of metal coagulant into the raw water and minimization of the time lag between the metering unit and feeding point—high dilution actually clogs the coagulant feed line because of metal hydroxide formation. There are a number of case histories proving this point. In the case of liquid alum, the pH of the diluted water should be less than 3.0 and the diluted solution of ferric coagulant should have a pH of less than 1.5. Thus, it is the author's belief that it is always better to feed neat solution into the flash mixing unit.

The initial (flash) mixer is often designed with a powerful mechanical mixer housed in a tank, providing greater than 15 s of hydraulic detention time; this type of mixing process is classified as a back-mixing reactor. Unfortunately, back-mixing causes a significant amount of the added metal coagulant to be preferentially absorbed by pre-formed flocs in the tank instead of suspended solids in the raw water; extra coagulant is therefore required to achieve good coagulation. For these reasons, many plant operators do not run the back-mixing reactor due to its ineffectiveness.

Figure 2 illustrates the conceptual coagulant dispersion patterns for three basic types of jet diffusion type flash mixers. This is based on the design and performance of 40 actual installations since 1974. Type 1 is multi-jet diffusion, type 2 is a target plate type of jet diffusion, and type 3 is a 'Deluge' jet type of diffusion flash mixer. The type 2 flash mixing system is the proprietary item of Montgomery Watson, Inc. in the United States.

The type 1 mixing system (Chao and Stone 1979) consists of two sets of multi-nozzles; one set dispersing alum to the peripheral zone and the other covering the middle portion of the pipe. This design depends on the deflection of the jets containing coagulant by the plant design flow rate. The wakes produced by the jets create a nearly uniform dispersion of coagulant. However, if the plant flow rate is lower than the designed flow rate, the jets will not be deflected as anticipated, thus the jet velocity must be constantly adjusted to the flow rate of the raw water. When the plant flow rate is further decreased all the jets will hit the side wall of the pipe, uniform dispersion of the coagulant essentially does not occur, and a heavy layer of alum sludge forms on the pipe walls. It is important to note that this type of mixing system will have its nozzles clogged by debris and fish if raw water is used as the source of the pressurized water unless fine strainers are installed before the jet nozzles.

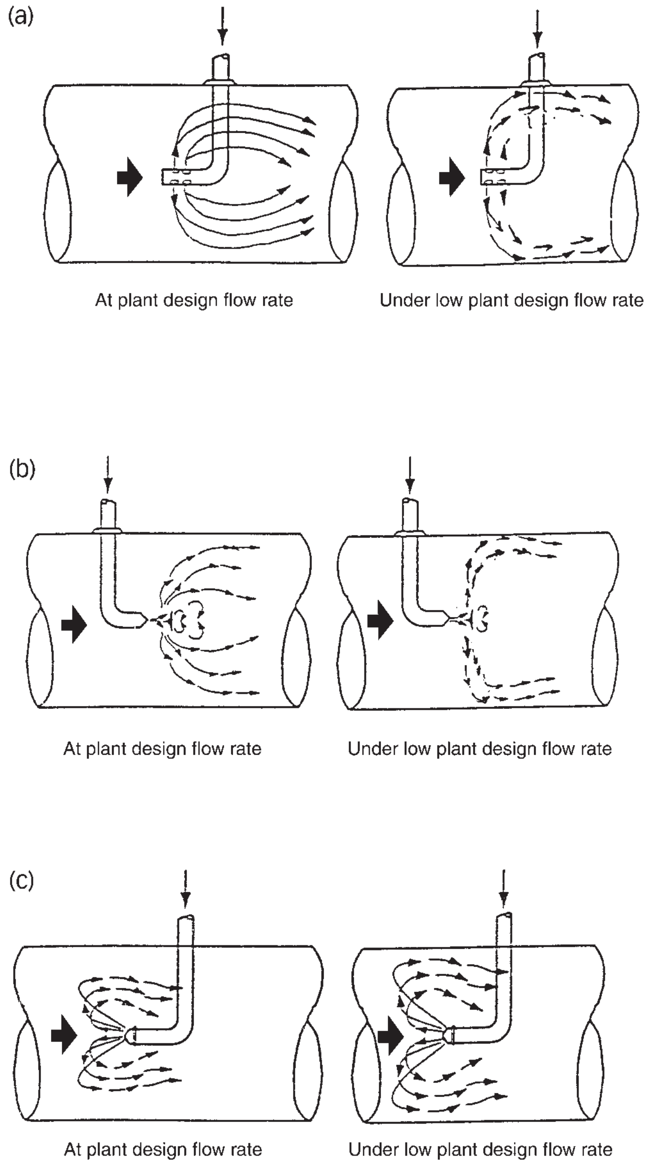


Figure 2 | Mixing pattern of three types of jet diffusion. (a) Type 1: two sets of multi-jets diffusion type (jet velocities: 40 fps and 25 fps); (b) Type 2: a single jet with a target plate type (jet velocity: 25 fps to 30 fps); (c) Type 3: a single full cone 'deluge' jet type (90° spray angle, 25 fps at nozzle). Note: coagulant is fed at the jet nozzle for all types

 Journal of Water Supply: Research and Technology—AQUA | 49.6 | 2000

The type 2 mixing system shares the same basic concept as the multi-jet diffusion system (type 1), but places a target plate in front of a jet emanating from a single nozzle. The target plate deflects the jet and the velocity of the raw water disperses the coagulant throughout the process water. A hydraulic model study using a 150 mm pipe with tracer demonstrated that, under optimum conditions, good mixing is achieved within one pipe diameter downstream of the target plate. However, when the plant flow rate drops off, this type of mixing system experiences the same problems as the type 1 mixing system unless the jet velocity is properly adjusted.

The type 3 mixing system is the original design of the jet diffusion mixer. A single full-cone jet nozzle with a minimum spray angle of 90° is placed at a counter-current direction. The nozzle does not produce a spray mist, but a strong deluge-type cone flow. Use of this type of nozzle as the surface wash nozzle in a pilot filter resulted in the strong, uniform agitation of the filter bed surface in a 6 inch filter column. One problem with this mixer is that it may not disperse coagulant in a uniform manner when the pipe diameter becomes large (over 6 feet or 1.8 m). Under a high raw water flow rate the coagulant will not be adequately dispersed close to the periphery of the pipe. On the other hand, the dispersion of coagulant during low plant flow rate is anticipated to be better than type 1 and type 2 at a constant jet velocity.

Based on the discussion of Figure 2, it is evident that one special design consideration for a jet diffusion flash mixer is the ability to change the jet velocity according to the plant flow rate. If the source of the pressurized water is supplied at a constant flow rate, it is important to install a flow meter and flow regulating valve in the pressured water supply line. If a pump is the source of the pressured water supply, a variable frequency drive may be used to control the flow rate. Generally, good dispersion of coagulant is achieved when the momentum ratio of the plant flow rate and the jet flow ranges from about 10:1 to 10:1.5. Another rule of thumb is to design the proportion of the jet flow rate to be approximately 2–4% of the plant flow rate.

Special attention to flow conditions upstream of the jet diffusion mixer is not necessary for all plants but is occasionally an important issue. If the immediate upstream flow condition of the mixer is not a straight pipeline but and an elbow or a sharp turn, the flow pattern at the mixer location is distorted. Consequently, the mixer cannot uniformly disperse coagulant within a short period of time. In these cases, it is absolutely necessary to add a flow straightening VANE system upstream of the mixer or add a secondary mixer just downstream of the mixer. A simple method of achieving auxiliary mixing is the installation of an orifice plate approximately one pipe diameter downstream of the jet mixer. Conceptually, the orifice plate should be effective in minimizing excessive distribution of alum to the zone near the pipe wall for both type 1 and type 2 mixing systems when the plant flow rate is low (see Figure 3). An approximate guide, created by the author, is 9–18 inches (23–46 cm) of headloss at the plant flow rate. The precise size and location of the orifice is dependent on the site location and may be determined through hydraulic scale model studies or the finite element method of analysis.

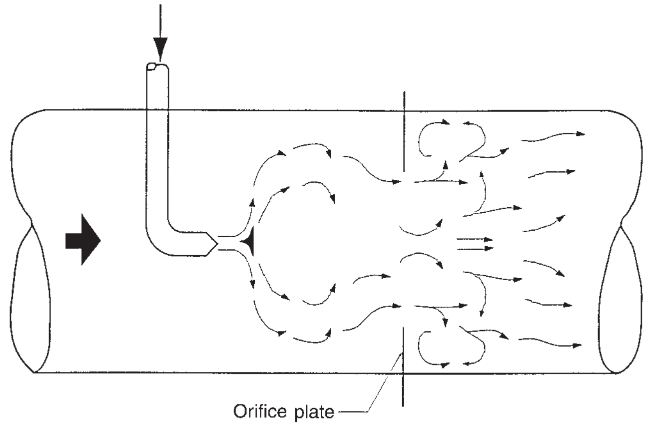


Figure 3 | Effect of orifice plate as supplemental mixing device (concept).

GENERAL DESIGN CRITERIA AND RECOMMENDATIONS

The recommended design criteria for the jet diffusion flash mixing system are:

Mixing energy (G) 750–1,000 s^{-1}

Mixing time	1 s or less at the plant design flow rate
Water jet velocity	20–30 fps (6–9 m s^{-1})
Ratio of process flow rate to jet flow rate	1:0.02 to 1:0.04

Note: the mixing zone is 1–1.25 pipe diameters from the tip of the nozzle (based on a hydraulic model study).

Scientifically, the design of a jet mixing system is subject to finite element analysis of the mixing flow pattern, establishing the proper shape of the jets and proper shape of deflector plates, and determining the momentum ratio of the jet flow rate and the flow rate of the process water. For example, in a system composed of a single jet with a target plate (type 2 of Figure 2), the shape and size of the target plate as well as the location of the plate are subject to hydraulic scale model study or finite element analysis whenever the design is elaborated. However, the rather simple design criteria presented in this section are useful in choosing between the three types of jet diffusion systems illustrated in Figure 2.

Designing a jet diffusion system does not require exceptional knowledge. The design may be derived through the use of strict scientific theory and analysis with the aid of the recommended design criteria.

A word of caution with regard to the over-emphasis of the coagulation theory and the ideal design: there are many case histories of conventional treatment process plants which were either poorly designed or constructed without flash mixing systems, yet these plants are capable of producing quite acceptable flocculation, sedimentation, and filter performance. Many treatment plants with traditional complete treatment processes (which produce sweep floc) as well as ‘reactor-clarifiers’, which often do not have a flash mixer, have demonstrated good sedimentation and filter performance. Moreover, Kawamura (1996), Amirtharajah and Mills (1982) and Clark *et al.* (1994) have found that flash mixing has little effect on settled water quality when operating under conditions of enhanced coagulation: defined by the United States Environmental Protection Agency (USEPA) as the over-feeding of coagulant to produce sweep flocs. The enhanced coagulation process produces an overwhelming amount of hydroxo-compounds under a pH of approximately 6.0 and coagulation and flocculation occur simultaneously. Thus, the effectiveness of flash mixing is not clearly evidenced. The shortcoming of these plants is that they require 25–30% more coagulant and therefore produce a proportionally excessive amount of sludge. Feeding cationic polymer with metallic coagulant yields savings in metallic coagulant dosage and reduces the amount of sludge production.

The important design features of the jet diffusion type of flash mixing system include:

1. Coagulant should be added in front of the jet and inorganic coagulant should not be fed to the pressured water supply line upstream of the jet otherwise the jet orifice will clog.
2. Design an adjustable mixing flow rate and install a flow meter to indicate flow rate.
3. Furnish a pressure gauge in the pressure water supply line to detect clogged jet nozzles.
4. Furnish an in-line screen of appropriately sized openings (at least 0.25 inch or 6 mm) to prevent the jet orifice from becoming clogged by fish and other debris if raw water is used as the mixing water.
5. Firmly secure all parts of the system and do not allow vibration to occur.
6. Provide access to the jet orifice system or construct a retractable system for inspection and maintenance.

An ideal arrangement is to install a single jet dispersion head for the entire processing water pipe or channel. Experience has shown that a single jet dispersion head is effective for diameters up to approximately 6 feet (1.8 m); any larger may require multi-jet heads to ensure instant and uniform dispersion of coagulant. However, the use of multiple dispersion heads requires a more complicated design since the coagulant must be distributed in equal amounts to each head and the inorganic coagulant is ideally fed as neat solution to avoid formation of scale in the feed line. Thus, the flow rate of the coagulant solution must be quite low under low dosage and low plant flow rate. As previously noted, the preferred momentum ratio of the processing water flow rate and the flow rate of the dispersion jet should be in the range of 10:1 to 10:1.5.

It is important to monitor the reliability of the coagulation and flocculation processes. Thus, installation of a streaming current detector (SCD) unit just downstream of

Table 3 | Design criteria of jet diffusion flash mixing system: Henry Mills Water Filtration Plant

Size (cross-section) of raw water conduit	12 ft × 12 ft (3.7 m × 3.7 m)
Water passage area at point of mixing (orifice)	9 ft diameter (2.75 m)
Mixing energy (G)	750 s^{-1} at plant design flow rate
Mixing time (A)	Approximately 1 s
Total number of pumps	3 (one is standby)
Pump capacity (each)	3,000 gpm (11.4 m^3 min^{-1})
Horse power of each pump motor	50 hp (37.5 kWh)

the flash mixer is highly recommended. This will allow operators to check for proper coagulant dosage.

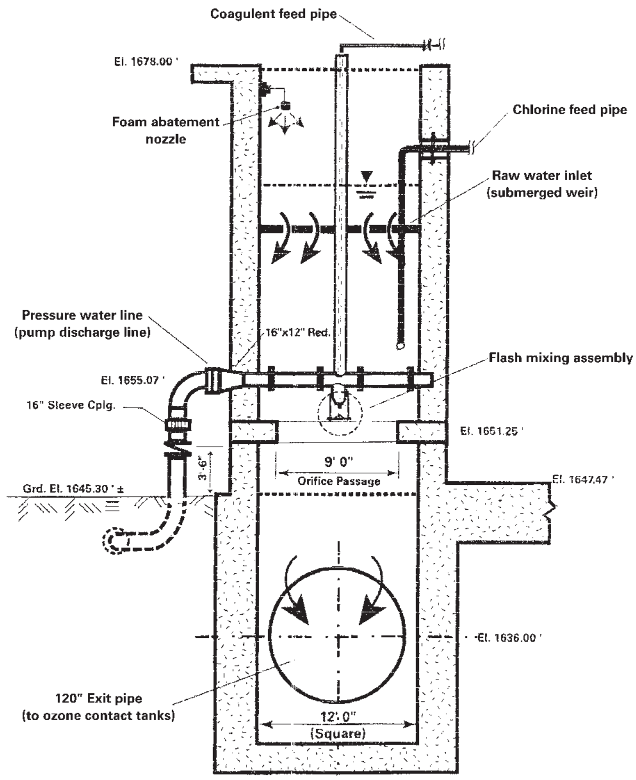


Figure 4 | General view of jet diffusion flash mixing system.

EXAMPLES OF RECENT DESIGN

The design criteria and performance of the jet diffusion flash mixing units of two large water treatment plants are presented. The Henry Mills Filtration Plant (330 mgd or 1,250 ML day^{-1}) of the Metropolitan Water District of Southern California has a conventional treatment process train; the Prospect Water Treatment Plant (790 mgd or 3,000 ML day^{-1}) of Sydney, Australia has a direct filtration process. Data were obtained after the plants had been on-line for a period of two years.

The Henry Mills Plant system design requires special consideration due to the following conditions (see Table 3). The location of the flash mixing unit is a vertical conduit with a 12 feet by 12 feet (3.7 m by 3.7 m) cross-section with about 40 feet (12 m) of flow length. The raw water flows into this conduit from a submerged weir 12 feet (3.7 m) in length, located at one side of the upper conduit wall. Consequently the flow characteristic in this vertical conduit is not plug flow at the flash mixing location which is approximately 15 feet (4.5 m) below the elevation of the inlet weir. Due to the square cross-section of the raw water conduit, circular dispersion of the coagulant by a jet mixing system may fail to adequately distribute coagulant to the four corners. Thus, a significant volume of raw water could short-circuit through the corners without coagulant.

Based on these unique conditions, an orifice passage with a diameter of 9 feet (2.75 m) is provided at the flash mixing location; the design scheme is presented in Figure 3. Actual designs are shown in Figures 4 and 5. Since the orifice produces 2 feet (0.61 m) of headloss, the mixing energy (G), at the plant design flow rate, is approximately 370 s^{-1} for the orifice itself. A photograph of the system during construction is presented in Figure 6.

The Henry Mills Plant was expanded from 110 mgd (417 ML day^{-1}) to 330 mgd (1,250 ML day^{-1}). The original flash mixing system (multi-jet flow and pressure control sluice gates) was changed to the new jet dispersion

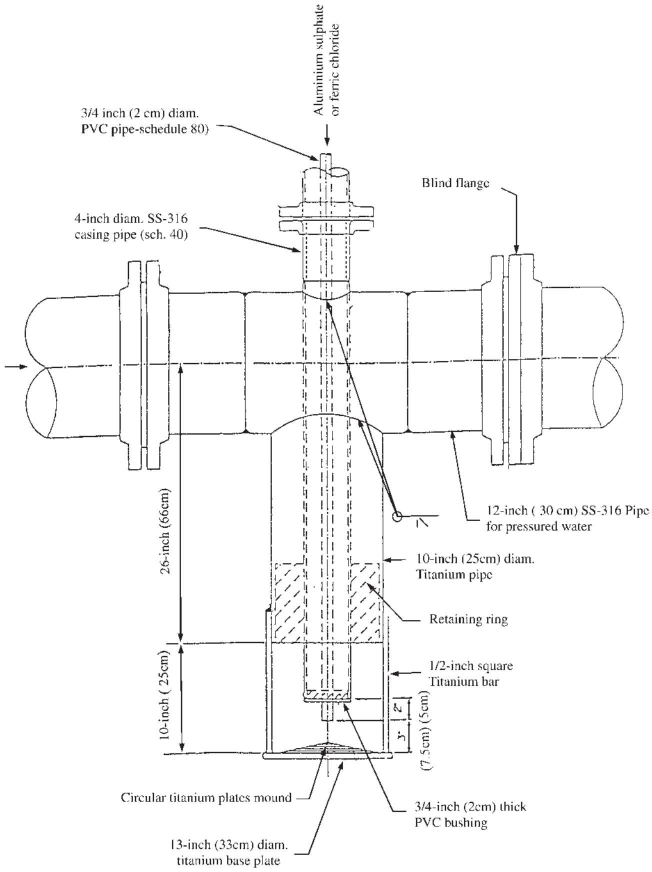


Figure 5 | A detailed view of jet diffusion mixing assembly.

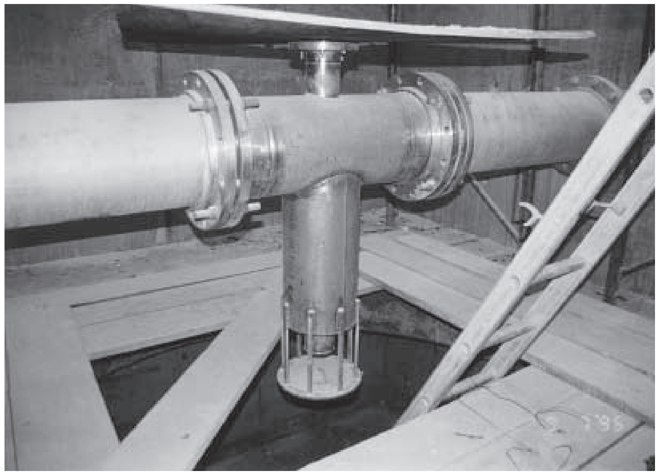


Figure 6 | The flash mixing system during construction.

Table 4 | Design criteria of flash mixing system: Prospect Water Filtration Plant

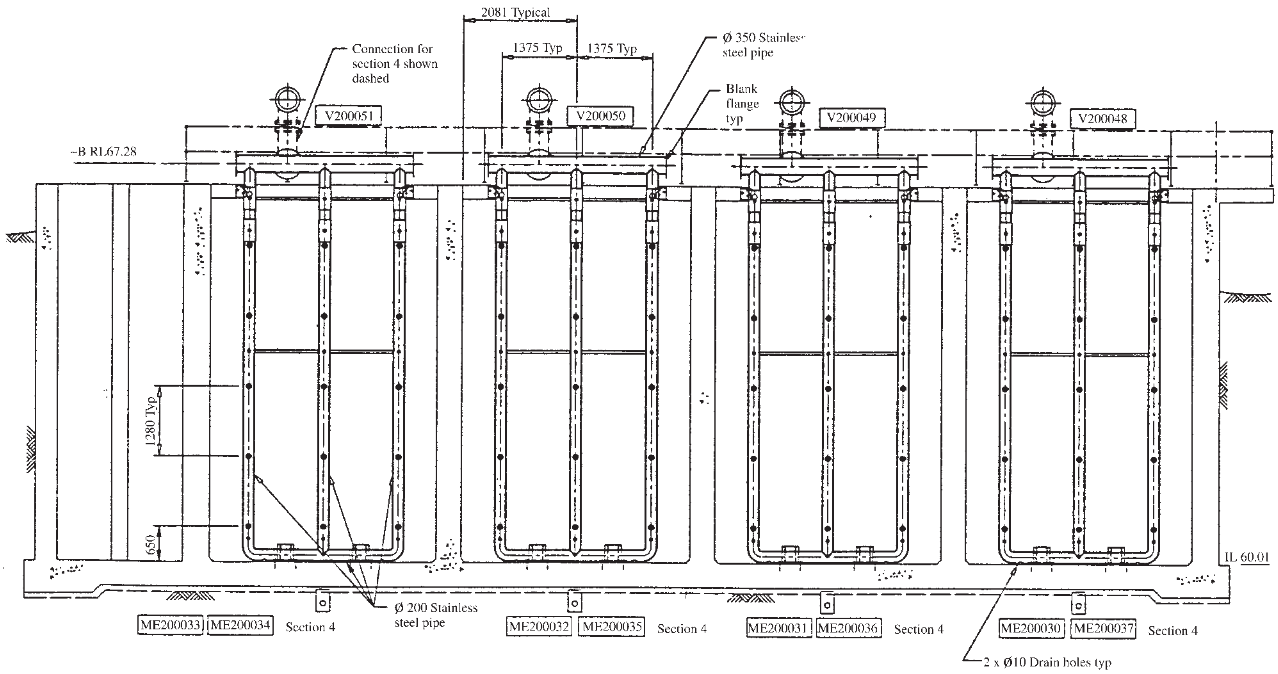
Number of raw water channels	4
Size and shape of each channel	13.5 ft (w) and 19.5 ft (H), (4.1 m × 6 m)
Type of mixing	Water jets with target plates
Mixing energy	750 s^{-1}, average
Number of mixing jets	15 jets for each channel
Mixing time	1–2 s

flash mixing system in June 1996 after the expansion project was completed.

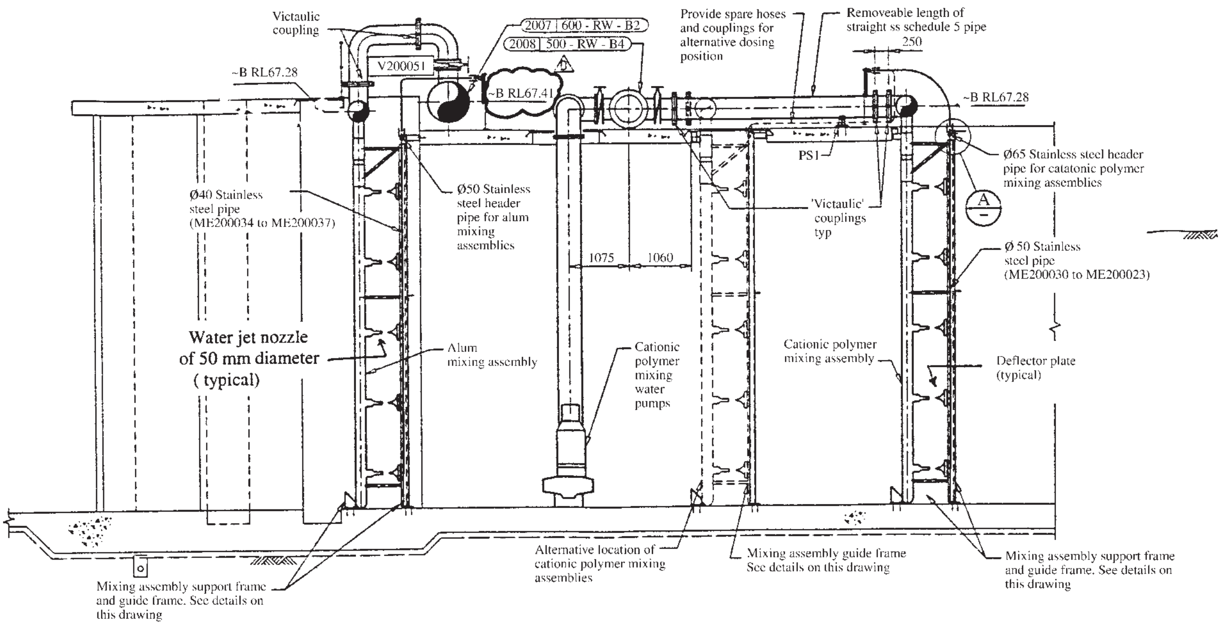
The plant's operational logs demonstrate that after July 1996, the turbidity of the settled water was consistently better with a 15–25% decrease in alum feed rate. The average turbidity was approximately 1 ntu, compared with 2–3 ntu prior to modification of the flash mixer under similar plant operational conditions. The ratio of the pump motor horsepower to the plant flow rate was 0.3 hp per mgd (5.9 kW 100 ML^{-1}) as presented in Table 2.

The Prospect Water Filtration Plant of Sydney, Australia is a 790 mgd (3,000 ML day^{-1}) direct filtration process plant that can be expanded to 1,100 mgd (4,200 ML day^{-1}). It is operated as a 'design-build-own' project with Lyonnaise des Eaux and two Australian companies, P&O Australia and Lend Lease Corp, as the key parties involved in the process. Sinclair & Knight and Camp Scott Murphy of Australia are responsible for the design component, along with US firms Montgomery Watson and Camp, Dresser & McKee. The plant began operation in August 1996 and the performance of the flash mixing system is reported great saving 20 percent reduction of coagulant usage in order to produce an optimum filter influent water quality.

The Prospect Water Filtration Plant has four independent filtration channels (see Table 4). Each channel is 13.5 feet wide and 19.5 feet high (4.1 m × 6 m). The size and shape of each channel prohibits the use of a single head jet dispersion system. Consequently, the flash mixing system is designed as three 16 inch (400 mm) pressured water



Water jet flash mixing assembly in the inlet channel
- cross section of the channel -



A side view of the jet mixing assembly

Figure 7 | General arrangement of flash mixing system.

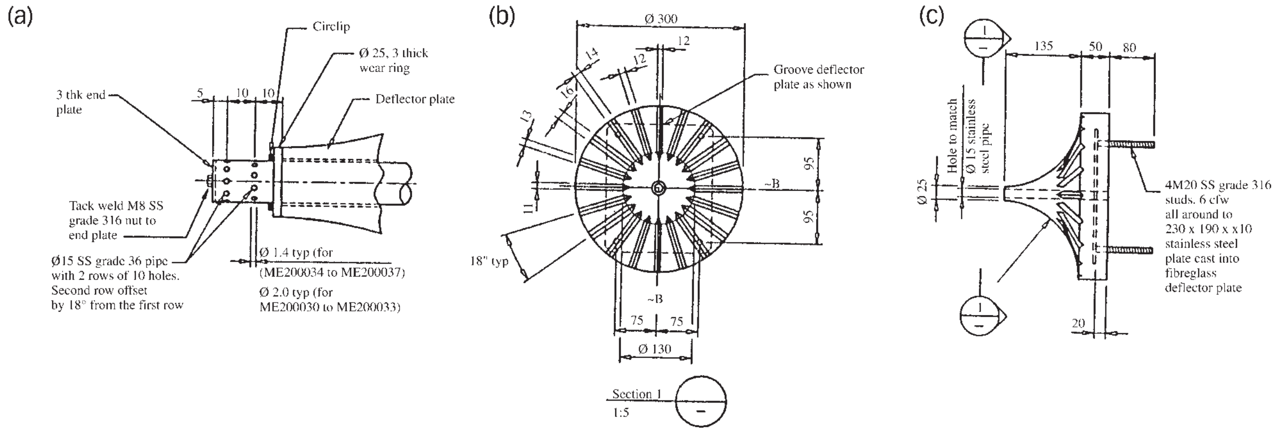


Figure 8 | Partial view of jet mixing assembly: (a) detail of chemical feed orifices at the tip of deflector plate, (b) deflector plate detail.

supply pipes arranged vertically; each vertical pipe has five jet orifices with a target plate. The total number of jets per channel is 15 with a total of 60 jets for this plant. Figure 7 depicts a general arrangement that was designed based on the results of a hydraulic scale model study and Figure 8 presents some details of the flash mixing system.

The velocity of the water jet is selected as 43 fps (13 m s^{-1}) and each of the four channels has a submersible pump to produce the water jets. Each pump is sized at 8.3 mgd at 27 feet of total dynamic head (365 l s^{-1} at 90 kPa TDH) with a 50 hp (37 kW) electrical motor. Since this 790 mgd (3,000 ML day^{-1}) plant requires a total of four pumps for flash mixing, the ratio of power requirement to the plant flow rate is 0.25 hp per mgd (4.93 kW 100 ML^{-1}.

SUMMARY AND CONCLUSIONS

Proper design of the flash mixing system for coagulant mixing is important in the overall effectiveness of water treatment. Jet diffusion type flash mixing systems have proved to be effective since the mid-1970s. Generally speaking, a saving of 25–30% of alum can be achieved when compared with the ordinary back-mixing type flash mixing system. Good flash mixing is particularly important for in-line, as well as direct filtration processes, where coagulant dosages are limited to 3–5 mg l^{-1}, in order to ensure good filter performance. However, instant dispersion of coagulant becomes less important during enhanced coagulation where coagulant saving is not an issue.

The design of any system should be simple, reliable, cost-effective, and proven, with minimal operations and maintenance costs. The jet dispersion system is an effective coagulant flash mixing system that is capable of meeting all these requirements.

ACKNOWLEDGEMENTS

The author wishes to thank James Bishop, John Bednaski, and Ted Tanaka of the MWD of Southern California and Ken Waterhouse of Montgomery Watson's Sydney office for contributing to this article.

REFERENCES

Amirthrajah, A. 1979 Design of rapid mix unit. In *Water Treatment Plant Design*, Sank, R.L. (ed.) Ann Arbor Science, Michigan.

Amirthrajah, A. & Mills, K. M. 1982 Rapid mixing design for mechanism of alum coagulation. *J. Am. Wat. Wks Assoc.* **74**(4), 210.

ASCE 1940 *Water Treatment Plant Design,* ASCE-Manual of Engineering Practice, No.19. American Society of Civil Engineers Reston, USA.

ASCE/AWWA 1997 *Water Treatment Plant Design*, ASCE-Manual of Engineering Practice, 2nd and 3rd Editions. American Society of Civil Engineers, Reston, USA.

ASCE, CSSE, AWWA 1969 *Water Treatment Plant Design.* American Water Works Association, New York.

AWWA Research Foundation Report 1991 *Mixing in Coagulation and Flocculation*. American Water Works Association, New York.

Black, A. P. 1960 Basic mechanisms of coagulation. *J. Am. Wat. Wks Assoc.* **52**, 492.

Chao, J. L. & Stone, B. G. 1979 Initial mixing by jet injection blending. *J. Am. Wat. Wks Assoc.* **71**, 570–573.

Clark, M. M., Amirthrajah, A. & Trussell, R. R. 1994 *Selection and Design of Mixing Process for Coagulation.* American Water Works Association Research Foundation.

Great Lakes–Upper Mississippi River Board of State Sanitary Engineers 1992 *Recommended Standards for Water Works.* Health Education Service.

Hardy, W. 1900 Fine Vorlauefige Untersuchung der Bedingungen 2. *Phys. Chem*. **33**, 385.

Kawamura, S. 1973 Coagulation consideration. *J. Am. Wat. Wks Assoc.* **65**(6), 417–423.

Kawamura, S. 1976 Considerations on improving flocculation. *J. Am. Wat. Wks Assoc.* **68**(6), 328–336.

Kawamura, S. 1991 *Integrated Design of Water Treatment Facilities.* John Wiley & Sons, New York.

Kawamura, S. 1996 Optimization of basic water treatment processes–design and operation: coagulation and flocculation. *J. Wat. Suppl.: Res. & Technol.–Aqua* **45**(1), 35–47.

Lang, J. S. & Kawamura, S. 1988 Improvements in flash mixer design. *1988 Annual AWWA Conference Proceedings, Part I, Sessions 1–21*, pp. 861–878.

JM Montgomery Consulting Engineers 1985 *Water Treatment Principles & Design.* John Wiley & Sons, New York.

Olin, H. H. & Gauler, J. V. 1938 The use of bentonite clays in water treatment. *J. Am. Wat. Wks Assoc.* **30**, 498.

Sayer, C. N. 1960 *Chemistry of Sanitary Engineers.* McGraw-Hill, New York.

Stumm, N. & O'Meria, C. R. 1968 Stoichiometry of Coagulation. *J. Am. Wat. Wks Assoc.* **59**, 514.

Weber, W. J. Jr 1972 *Physicochemical Processes for Water Quality Control*. Wiley International, New York.