# Coagulant mixing revisited: theory and practice

James K. Edzwald

## ABSTRACT

Are rapid-mixing tanks with intense mixing necessary? Intense mixing applies to the coagulation mechanism of charge-neutralization of negatively-charged particles, but this is not a common coagulation method. More common is precipitation of aluminum or iron for coagulation of particles and natural organic matter, which is often called sweep-floc coagulation. Coagulation by precipitation is indifferent to mixing intensity. Energy and cost savings are realized by designing mixing systems for coagulation that do not use tanks with mechanical mixers. Systems examined are hydraulic methods (weirs, Venturi meters, others) including the non-mechanical systems of pipe and open-channel static mixers. These systems provide sufficient mixing intensity for sweep-floc coagulation and for certain conditions provide sufficient mixing intensity for charge-neutralization coagulation with much less energy input. Mixing systems designed specifically for coagulant addition, such as rapid-mixing tanks and pipe and open-channel static mixers, should be sized based on the average daily flow not on the plant capacity flow. This produces sustainable designs with lower capital costs for all systems and lower operating costs for rapid-mixing tanks.

**Key words** | charge-neutralization of particles, coagulant precipitation, coagulation, mixing intensity, rapid mixing, sustainable design

**James K. Edzwald**
Department of Civil and Environmental
   Engineering,
University of Massachusetts,
Amherst,
MA 01003,
USA
E-mail: *Edzwald@ecs.umass.edu*

## NOTATION

| | |
|---|---|
| $C_{avg}$ | Average chemical or coagulant concentration |
| COV | Coefficient of variation |
| $G$ | Root-mean-square velocity gradient |
| $g$ | Constant for gravitational acceleration, 9.81 m/s$^2$ |
| $h$ | Change in hydraulic head |
| $P$ | Power input |
| $Q$ | Volumetric flow rate |
| $\bar{t}$ | Mean water detention time |
| $V$ | Mixing volume |
| $\varepsilon$ | Net rate of energy dissipation per unit water mass |
| $\eta$ | Kolmogorov average-length eddy scale |
| $\rho_w$ | Water density |
| $\sigma$ | Standard deviation of the chemical (coagulant) concentration |
| $\tau_\eta$ | Kolmogorov average-time scale |
| $\mu_w$ | Dynamic water viscosity |
| $\upsilon_w$ | Kinematic water viscosity |

## INTRODUCTION

The term rapid mixing (sometimes called flash mixing) has been used in water treatment practice for the last 50 years to describe the process of coagulant addition. Furthermore, it is usually stated that the mixing must be intense or violent and of short duration. A rapid-mixing tank with mechanical mixers is often depicted as the means to accomplish this process.

The author has visited many water plants around the world where coagulants are added without a rapid-mixing tank. In many plants with rapid-mixing tanks, the plant operators have turned off the mixers and add the coagulant to the plant influent or just ahead of the tank and have seen no change in plant performance compared to use of the rapid-mixing tanks with the mixers in operation. Furthermore, we do add various chemicals within a water plant without using a mixing tank. Examples include: acids ($H_2SO_4$, $CO_2$), bases (NaOH,

Ca(OH)₂), disinfectants (chlorine, chlorine dioxide), fluoride, and corrosion inhibitors. Why then do we often build rapid-mixing tanks and install mechanical mixers for coagulant addition? It turns out that intense mixing is not necessary except for one type of coagulation mechanism, and the use of intense mixing has contributed to a misunderstanding of how coagulation works. It has also led to water plants using more mechanical energy than necessary. When the coagulation mechanism involves precipitation of the metal coagulant, which is typically the case, then the chemical conditions are important and intense mixing is not required. The objective for coagulant addition (mixing) is simply to achieve a uniform concentration of coagulant in a short time within the flow undergoing treatment, and high-mixing intensity is not necessary.

The objectives of the paper are: (1) to show that the coagulation mechanism of charge-neutralization of particles that calls for intense mixing conditions has limited application, and (2) to show that there are alternatives to rapid-mixing tanks such as various hydraulic methods or the use of open-channel static mixers that provide adequate mixing conditions for coagulant addition. The paper is laid out in the following manner. First, the basic equations describing mixing intensity are presented. A short section follows on the practice of coagulant mixing. Third, coagulation mechanisms and mixing theory are described and evaluated. Fourth, an evaluation of mixing intensity is presented for rapid-mixing tanks and for hydraulic methods of coagulant mixing. Finally, several important conclusions and applications to water treatment practice are listed.

## BASIC EQUATIONS FOR DESCRIBING MIXING INTENSITY

In water treatment practice, Camp's root-mean-square velocity gradient ($G$) is used to characterize mixing intensity (Camp & Stein 1943). It is a global measure of mixing, and thus does not account for the considerable variation in mixing that occurs within the system. Camp developed $G$ for characterizing mixing for various applications including rapid mixing with mechanical mixers, rapid mixing

produced through changes in hydraulic head, and for flocculation tanks.

### Rapid-mixing tanks

Equation (1) has general application for characterizing mixing intensity. Here, we apply Equation (1) for evaluation of rapid-mixing tanks and so the power input ($P$) is that supplied by mechanical mixers – actually, it is the energy dissipation rate or power transferred to the water.

$$G = \left(\frac{P}{\mu_w V}\right)^{1/2} \tag{1}$$

### Kolmogorov and eddy scales

About the same time as Camp, the Russian mathematician Kolmogorov developed fundamental theory and mathematical expressions describing mixing intensity in terms of the scales of eddies (Amirtharajah & Trusler 1986; Amirtharajah & Tambo 1991; MWH 2012). Eddies are formed from turbulent mixing, and the energy is transferred from larger eddies to smaller ones until energy dissipation occurs through viscous forces as depicted in Figure 1. The Kolmogorov theory relates the average-length eddy scale ($\eta$) through Equation (2) and the average-time scale ($\tau_\eta$) through Equation (3) to the kinematic viscosity ($v_w$) and the net rate of energy dissipation per unit water mass ($\varepsilon$).

$$\eta = \left(\frac{v_w^3}{\varepsilon}\right)^{1/4} \tag{2}$$

$$\tau_\eta = \left(\frac{v_w}{\varepsilon}\right)^{1/2} \tag{3}$$

These are fundamental equations that give the smallest scales of turbulent mixing. The length microscale ($\eta$) indicates a division between large eddy sizes and small eddies where viscous dissipation occurs. Working with Equation (3) and recognizing that $\varepsilon$ is the power transferred per mass of water and substituting for $v_w$ as equal to $\mu_w$ divided by the water density, it is shown through Equation (4) that
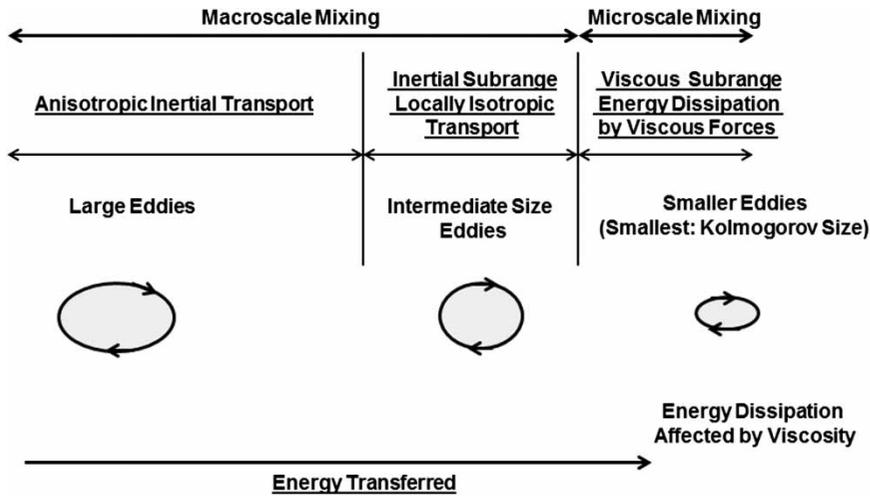
**Figure 1** | Concept of turbulent mixing and eddy scales of energy dissipation (adapted from MWH (2012)).

Camp's $G$ is the inverse of the Kolmogorov time scale.

$$G = \frac{1}{\tau_\eta} = \left(\frac{\varepsilon}{\nu_w}\right)^{1/2} = \left(\frac{P}{\mu_w V}\right)^{1/2} \tag{4}$$

## PRACTICE OF COAGULANT MIXING

It is instructive to summarize the recommended mixing intensity and detention times for coagulant mixing in water treatment practice. One can then later compare these to the theory regarding intensity and coagulation mechanisms, and examine alternatives. Common design guidelines call for intense mixing with $G > 750 \, s^{-1}$ and detention time ($\bar{t}$) of 10–30 s in Ten State Standards (2007) and $G$ of 600–1,000 $s^{-1}$ and detention time of 10–60 s in AWWA-ASCE (2012). These design criteria are presented for rapid-mixing tanks with mechanical mixers, and the applicable coagulation mechanism is not mentioned. As pointed out later, Amirtharajah & Mills (1982) distinguish mixing requirements according to the coagulation mechanism and call for intense mixing for charge-neutralization while coagulation by precipitation is indifferent to mixing intensity. Furthermore, they give $G$ values for charge-neutralization coagulation within the range specified above for rapid mixing tanks, and even greater $G$ values are presented for static mixers (Amirtharajah & Trusler 1986; Amirtharajah & O'Melia 1990).

Contrary to the high $G$ values recommended above, Kawamura (2000) gives a much lower guideline for $G$ of 300 $s^{-1}$ for rapid-mixing basins and recommends detention times of 10–30 s.

## COAGULATION MECHANISMS AND MIXING THEORY

There are two coagulation mechanisms to consider. The theory pertaining to the destabilization of particles in the source water by charge-neutralization indicates that the efficiency of destabilization depends on mixing intensity. The other mechanism involves precipitation of the coagulant metal into a solid phase, referred to as sweep-floc coagulation. For this mechanism, the efficiency of coagulation does not depend on mixing intensity.

### Charge-neutralization of particles

This mechanism assumes that only the particles in the source water are being treated by coagulation. Here, the coagulant contains positively-charged species that adsorb onto the negatively-charged particles. At the proper coagulant dose, there is sufficient adsorption to produce a net-particle charge near zero. With the charge-neutralization coagulation mechanism there is little or no complexation between the coagulant metal and dissolved natural organic

matter (NOM) acting as a ligand. The concept of intense mixing with respect to this mechanism follows.

In their landmark paper, Amirtharajah & Mills (1982) used alum to describe hydrolysis of Al and formation of cationic species (pH conditions at which they exist is discussed below) at a time scale less than a second, as depicted in Figure 2. The idea then is to achieve high particle destabilization rates with the adsorption of the positively-charged coagulant onto negatively-charged particles by intense mixing so that the microscale eddy is small and mass transport of the coagulant species to the particle surface is favored by turbulent diffusion, as shown previously in Figure 1. The idea is to adsorb the positively-charged coagulant species to the particles before precipitation of the metal occurs. Furthermore, considering the time scale of producing the positively-charged species and that the adsorption reaction is assumed to be irreversible, then one concludes that both intense mixing and short mixing times are desired. This concept also applies to the use of polyaluminum chlorides (PACls) and organic cationic polymers as coagulants. In the first case, the primary aluminum polymer ($Al_{13}O_4(OH)_{24}^{7+}$) would be formed in a time scale of a second or less. For organic-cationic polymers, these polymers are present in the feed solution and so are initially available for adsorption and charge-neutralization.

Experimental evidence is presented by Amirtharajah & Mills (1982), Amirtharajah & Trusler (1986), and Klute & Amirtharajah (1991) for the intense mixing requirements for low alum doses and for organic cationic polymers in direct filtration applications. Amirtharajah & Trusler (1986) investigated destabilization rates as a function of the eddy sizes in accordance with Kolmogorov microscale theory and showed that mixing conditions that produced eddy sizes ($\eta$) of about 1–3 times the particle size should be avoided. They found for alum, used under charge-neutralization conditions, that destabilization rates using rapid-

**Figure 2** | Al hydrolysis and time scale of reaction for adsorption onto and charge-neutralization of negatively-charged particles (other in the figure can be $Al_{13}O_4(OH)_{24}^{7+}$ for polyaluminum chlorides) followed by time scale for possible metal precipitation.

mixing tanks were enhanced for intense mixing with $G$ of 700–1,000 s$^{-1}$.

## Applications and limitation of charge-neutralization coagulation and mixing

The charge-neutralization mechanism applies only to water supplies with low dissolved organic carbon (DOC) so that the coagulation objective is limited to destabilizing and removing particles; removal of DOC by coagulation does not apply. It applies to the use of alum under acidic pH conditions and for PACls so that positively-charged species (for example, $Al(OH)^{2+}$ and $Al(OH)_2^+$ for alum or $Al_{13}O_4(OH)_{24}^{7+}$ for PACl) dominate for charge-neutralization as depicted in Figure 2. Specific conditions of alum use would be restricted to doses less than 1 mg/L as Al and acidic pH conditions (about pH 6 or less) to avoid metal precipitation as the main coagulation mechanism. If one uses alum at pH near 6 and less, then one can use higher doses and avoid metal precipitation, but this practice can lead to high residual Al (Pernitsky & Edzwald 2006). For PACls, the desired pH conditions for charge-neutralization are in the mid 7s or less. Practically, the PACl dose should be kept low. Charge-neutralization coagulation also applies to the use of cationic organic polyelectrolytes (polymers) at low-product mass concentrations of a few mg/L or less. Some literature claims that charge-neutralization of particles using iron coagulants also applies; however, the author disagrees because Fe is so insoluble it is difficult to avoid precipitation unless used at acidic pH conditions (less than 5) at low concentration.

Overall, the charge-neutralization application is restricted mainly to direct filtration to treat low turbidity and low total organic carbon (TOC) water supplies. Another possible application is the coagulation of solids in softening plants if one uses an organic-cationic polymer.

## Coagulation by metal precipitation

Most water supplies, say 90% or greater, have sufficient TOC (2–3 mg/L and greater) and a NOM composition so that the coagulant dose is controlled by the TOC, not particles. Furthermore, when the metal coagulant is added, it is complexed by organic ligands such as humic substances composing a fraction of the NOM, and it is not available
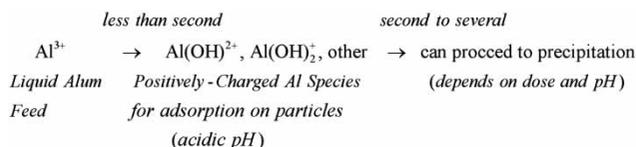
to adsorb on particles in a charge-neutralization mode. The DOC or TOC creates a coagulant demand that must be satisfied. When a sufficient metal coagulant dose is applied to satisfy this demand, then a solid phase is formed which we refer to as sweep-floc coagulation.

Figure 3 shows the sequence of reactions culminating in precipitation. Upon addition of the metal coagulant to the water flow, a series of chemical reactions occurs involving dissolved-metal-hydrolysis that occurs in microseconds, metal complexation with organic ligands (fraction of the DOC or NOM) that occurs in less than a second, and then precipitation of the solid phase that itself involves polymerization of the dissolved metal into large molecules leading to nucleation and formation of submicron particles, followed by growth of these particles. The overall reaction time of hydrolysis, metal complexation with organic matter, and precipitation takes several seconds; perhaps, tens of seconds for cold waters. In short, the metal coagulant (alum, Fe salts, and PACls) is used at dosages and pH conditions so that the coagulant demand of complexation is satisfied followed by formation of the controlling solid phase ($Al(OH)_3(s)$ or $Fe(OH)_3(s)$). Complexed NOM is removed by adsorption onto the solid phase or by co-precipitation of a mixed solid phase of the metal hydroxide and humic substances.

Unlike the charge-neutralization of particles coagulation scheme, mixing intensity does not affect coagulation performance. Far more important are the chemical conditions of dose and pH that bring about precipitation. The objective of mixing for sweep-floc coagulation is to achieve simply a uniform concentration of coagulant dose within the water flow in a short time. Low $G$ can be used as demonstrated by Amirtharajah & Mills (1982), where they showed no improvement for coagulation by sweep-floc treatment with $G$ of $300\ s^{-1}$ compared to mixing at higher $G$. In short, intense mixing is not required for sweep-floc coagulation, which is the most widely used coagulation-mechanism application. Furthermore, rapid-mixing basins with mechanical

mixers may be used but are not necessary, and so we can consider non-mechanical mixing methods and therefore reduce energy costs.
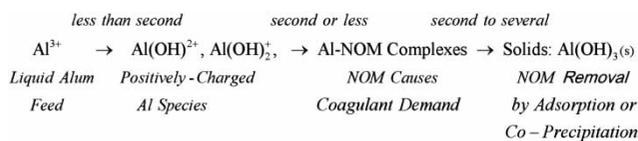
## Mixing characterization and intensity

For the coagulation mechanism of precipitation, intense mixing is not required. What is required is to achieve a uniform dose when the coagulant is added to the water flow, and it is desirable to achieve this in a small volume or short detention time. Some refer to this method of mixing as blending and by others as rapid blending (MWH 2012). We can use this terminology if we realize that we are not necessarily describing static mixers, which are sometimes called in-line blenders.

Mixing efficiency by blending is characterized by the ability to provide a uniform concentration of the coagulant dose in space and time by a statistical measure, the coefficient of variation ((COV), MWH 2012). COV is defined by Equation (5) where $\sigma$ is the standard deviation of the coagulant (or chemical) concentration (determined from numerous coagulant addition tests), and $C_{avg}$ is the average-coagulant concentration in the exit of the mixing system. The COV is referred to as the uniformity of mixing, where low values indicate little variance in the exit concentration or good uniformity of mixing. A common guideline is to specify a COV of 0.05 or less indicating very little variance in the coagulant concentration.

$$COV = \left(\frac{\sigma}{C_{avg}}\right) \qquad (5)$$

For in-line pressurized-pipe static mixers or open-channel static mixers, the design engineer can specify the desired COV, and the manufacturer can provide a suitable mixer. For pilot plants or full-scale water plants in which operators wish to determine the COV for coagulant addition to a Venturi meter, open channel, pipe bend or other method of mixing, they can take multiple samples at the exit of the mixing process and measure the coagulant concentration. They can then calculate $C_{avg}$ and the standard deviation from the measured data, and finally calculate COV from Equation (5). For new plants at the design stage, computational fluid dynamics (CFD) could be used to estimate

$$Al^{3+} \rightarrow Al(OH)^{2+}, Al(OH)_2^+, \rightarrow \text{Al-NOM Complexes} \rightarrow \text{Solids: } Al(OH)_3(s)$$

*less than second*     *second or less*     *second to several*

*Liquid Alum Feed*    *Positively - Charged Al Species*    *NOM Causes Coagulant Demand*    *NOM Removal by Adsorption or Co – Precipitation*

**Figure 3** │ Coagulation precipitation reaction and time scales involving hydrolysis, Al complexation with NOM, and precipitation.

the COV. Later, when the plant is built, the COV can be determined from measurements as described above, and compared to the CFD estimate.

Measurement of a metal coagulant in the exit of a mixing process can be difficult and inconvenient because of metal precipitation, an alternative is to use a tracer (such as fluoride) to determine COV.

COV is a good way to characterize mixing uniformity for coagulation in which the mechanism is precipitation. We cannot relate the COV to the widely used $G$ parameter; however, we know one does not require high $G$ values. As presented earlier, Amirtharajah & Mills (1982) showed that a low $G$ of 300 s$^{-1}$ was adequate for coagulation by coagulant-metal precipitation. Hence, later in the paper this $G$ value is used to evaluate low-intensity mixing conditions and to compare power requirements and costs to high-intensity mixing.

## EVALUATION OF MIXING INTENSITY, POWER, AND COSTS

A theme of the paper is that high-mixing intensity is not required for coagulation by metal precipitation (sweep-floc coagulation). Unfortunately, the practice of rapid mixing has been influenced by the theory of mixing intensity according to charge-neutralization of particles even though this coagulation mechanism is most often not applicable to water treatment. Below, high-mixing intensity (for charge-neutralization of particles) is compared against low-mixing intensity (for coagulation by precipitation). For the former, a $G$ of 750 s$^{-1}$ (widely cited as a typical design guideline, see earlier material) is used, and for the latter a $G$ of 300 s$^{-1}$ is used recognizing that even lower $G$ may be adequate if we were to use the COV to characterize the uniformity of mixing rather than $G$.

### Rapid-mixing tanks

Figure 4 shows the flow patterns produced by two types of mixers that are commonly used. These mixers can provide intense-mixing conditions. A single rapid-mixing stage is illustrated in the figure, but often rapid-mix tanks are baffled into two or three stages (all with mechanical mixers) allowing for coagulant addition, pH control with acid or base, and
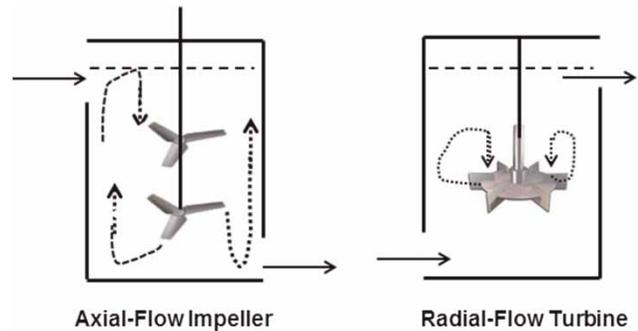


**Figure 4** │ Rapid-mixing tanks with axial-flow impeller and radial-flow turbine.

sometimes addition of organic polymers. In water treatment practice, the velocity gradient ($G$) is used to characterize the mixing intensity and is set at a design value. The power of the motors required is calculated from Equation (1) accounting for the efficiency in transferring energy to the water in the tank.

There are several disadvantages to rapid-mixing tanks as pointed out by Kawamura (2000) and MWH (2012). One major disadvantage of rapid-mixing tanks is that the power is being applied to a relatively large volume in order to house the mechanical mixer. This is inefficient because $G$ depends on the square root of the power supplied per water volume (Equation (1)) so larger volumes require more power to achieve a specified design value for $G$. Another disadvantage, common to all methods of coagulant mixing but a larger problem for rapid-mixing tanks with their larger volumes, is the plant capacity flow (maximum daily flow) is typically used to size the tank. The size should not be set based on the maximum daily flow. Coagulation is a chemical process and water plants adjust dose to the daily or hourly flow rate. Design criteria based on maximum daily flows using the detention times presented in the section, Practice of Coagulant Mixing, yield average daily detention times in rapid-mixing tanks some 1.5–2 times greater than the design criteria. So this works against what you are trying to achieve – short detention times are desired not longer. It is better to set the volume of rapid-mixing tanks based on the average daily flow. This would produce considerable reductions in size, capital costs, and energy costs as illustrated next.

Figure 5 illustrates the above shortcomings. Here, the power and energy costs for mechanical mixers are examined as a function of plant flow rate for the following conditions:
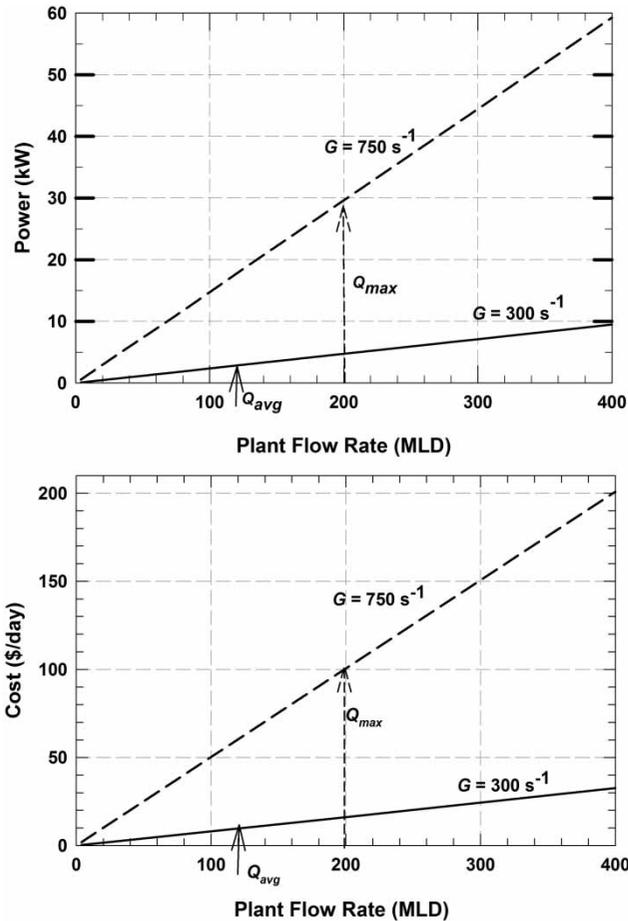
**Figure 5** │ Power and cost for mechanical mixing in rapid-mixing tanks (Conditions: detention time of 20 s, mixer-motor efficiency of 85%, temperature of 15 °C, and power cost of $0.12 per kWh). See the text for discussion of an example of designing for a maximum daily flow ($Q_{max}$) of 200 MLD compared to the average daily flow ($Q_{avg}$) of 120 MLD.

**Table 1** │ Size of rapid-mixing tanks based on maximum daily flow versus average daily flow for detention time of 20 s ($Q_{max}/Q_{avg} = 1.67$)

| Basis: maximum daily flow | | Basis: average daily flow | |
|---|---|---|---|
| $Q$ (MLD) | Volume (m³) | $Q$ (MLD) | Volume (m³) |
| 10 | 2.3 | 6.0 | 1.4 |
| 50 | 11.6 | 30 | 6.9 |
| 70 | 16.2 | 42 | 9.7 |
| 100 | 23.1 | 60 | 13.9 |
| 200 | 46.3 | 120 | 27.8 |
| 400 | 92.6 | 240 | 55.5 |

tanks using $Q_{max}$ versus $Q_{avg}$ for $Q_{max}/Q_{avg}$ of 1.67, which is a typical ratio. The results show that tanks are 60% smaller using $Q_{avg}$. To illustrate further the advantage of using the average daily flow, the power savings are compared for a plant with a $Q_{avg}$ of 120 MLD (million liters per day) compared to using a $Q_{max}$ of 200 MLD. From Figure 5, using $Q_{avg}$ of 120 MLD and the low-mixing intensity of 300 s⁻¹, the power requirement is 3.4 kW. On the other hand, if we design for a $Q_{max}$ of 200 MLD and high-intensity mixing of 750 s⁻¹, the power needed is 34.9 kW. This means a savings of one-tenth the power and applies to all cases where we use the average daily flow, and not the maximum daily flow, coupled with use of the low-mixing intensity of 300 s⁻¹ as opposed to the high-mixing intensity of 750 s⁻¹.

The bottom part of Figure 5 examines the power costs as a function of plant flow. As above, power requirements are 6.25 times greater for $G$ of 750 s⁻¹ compared to $G$ of 300 s⁻¹ and therefore so are power costs. Again, if we design $Q_{avg}$ of 120 MLD and the low-mixing intensity of 300 s⁻¹ we obtain a power cost of $9.60/day compared to a cost of $100.40/day with $Q_{max}$ of 200 MLD and high-intensity mixing of 750 s⁻¹. Overall, one obtains considerable savings in power requirements and costs (one-tenth) by using low-intensity mixing for the coagulation mechanism of precipitation (sweep-floc) and using the average daily flow rather than the maximum daily flow to size the mixing tank. The smaller rapid-mixing tanks, lower power use, and lower power costs can be incorporated into sustainable water plant designs.

Another point is that by designing the size of the rapid-mixing tank based on the average daily flow, then for greater plant flows the velocity gradient is not affected and the

a detention time of 20 s to size the volume of the tank, a mechanical motor efficiency of 85%, a water temperature of 15 °C, and power costs of $0.12 per kWh. Calculations are made for $G$ at 750 s⁻¹ (typical intense mixing), and a lower $G$ of 300 s⁻¹ that is considered for low-mixing intensity for coagulation by precipitation. In the top figure, while a $G$ of 750 s⁻¹ is 2.5 times greater than a $G$ of 300 s⁻¹, the power requirements are 6.25 times greater because the dependence varies by the square of the ratio of $G$ values. Consequently, using low mixing intensity results in a considerable reduction in power requirements.

Furthermore, as stated above, the average daily flow ($Q_{avg}$) should be used to size the tank, not the plant capacity or maximum daily flow ($Q_{max}$). Table 1 compares the size of

detention time decreases, which is beneficial for coagulation.

## Hydraulic methods of coagulant mixing

There are many non-mechanical or hydraulic methods that can be used to mix the coagulant. Two methods are illustrated in Figure 6: water falling over a weir and a Venturi meter. Other hydraulic methods include coagulant addition to a Parshall flume, to the plant inlet suction-side of pumps, and to the plant inlet with side-stream pump injection. One can also simply add coagulant to the plant influent and utilize the mixing produced by head loss in open channels or pipes with bends and turns coupled with water moving through valves.

In-line pressurized pipe static mixers have been used for many years to achieve mixing of coagulants. A picture of one is shown in the top part of Figure 7. They accomplish mixing of the coagulant by the use of internal baffles or vanes, which divide and recombine the water as it flows through the vanes.

The vanes are arranged into a series of elements, and elements can be removed for cleaning. Advantages are that there are no moving parts and no external energy usage. A disadvantage is the flow rate through water plants varies with demand affecting the head loss through the static mixer (varies with the square of the flow) and thus $G$ is similarly affected. In water treatment practice, they are often considered for smaller water plants for conditions of 0.6–1 m head loss and mixing times of 1–3 s Kawamura (2000).

A newer technology available to water plants is open-channel static mixers (see Figure 7). The head loss for these is an order-of-magnitude smaller (0.05–0.07 m) than that of pipe static mixers, and the variation in head loss with flow rate is small.

### Equations for $G$ for hydraulic methods

For the mixing achieved for hydraulic systems (water falling over a weir, the change in hydraulic head through a Venturi meter, head loss in open channels or in pipes with bends
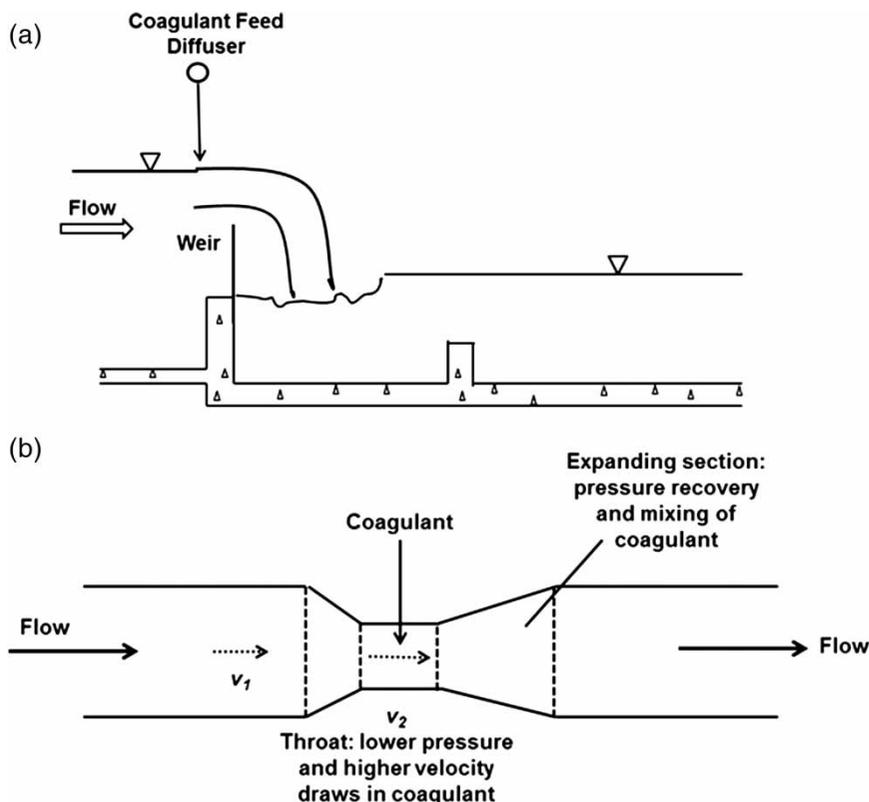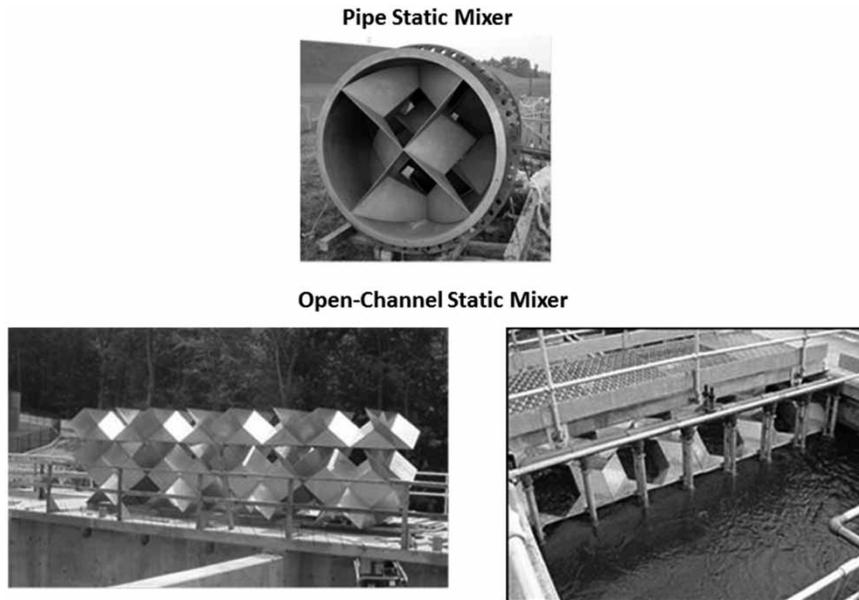


**Figure 6** | (a) Coagulant added to plant inlet weir, (b) coagulant addition to plant influent Venturi meter.

**Pipe Static Mixer**

**Open-Channel Static Mixer**



**Figure 7** | Pipe static mixer (Courtesy of Russell Jones, Hazen and Sawyer P.C.); open-channel static mixer prior to installation (left) and after installation (right) at Stamford, CT (Aquarion Water Company of CT, courtesy of Matthew T. Valade, Hazen and Sawyer P.C.).

and turns, and head loss through static mixers), the power is calculated from Equation (6), where $h$ is the change in hydraulic head. Substituting for $P$ in Equation (1), we obtain Equation (7) for $G$ for non-mechanical or hydraulic mixing processes, where $\bar{t}$ is the mean water detention time.

$$P = \rho_w g Q h \tag{6}$$

$$G = \left(\frac{\rho_w g Q h}{\mu_w V}\right)^{1/2} = \left(\frac{\rho_w g h}{\mu_w \bar{t}}\right)^{1/2} \tag{7}$$

From Equation (7) we see that $G$ depends on the energy transferred (dissipated) to the water per time. For rapid mixing tanks with volume ($V$) sufficient to house the mixer, one has relatively large $V$ and mixing time (10 s or more). However, with hydraulic mixing, the mixing times are small at about 1 to several seconds depending on the method. It is much more efficient to mix a small volume (small detention time) that one has with hydraulic methods than the large volume (large detention time) that one has with rapid-mixing tanks. With small detention times for hydraulic methods of mixing, we can achieve satisfactory $G$ values as illustrated next.

Figure 8 shows $G$ as a function of head loss for plant influent pipes and channels. Low head loss is expected
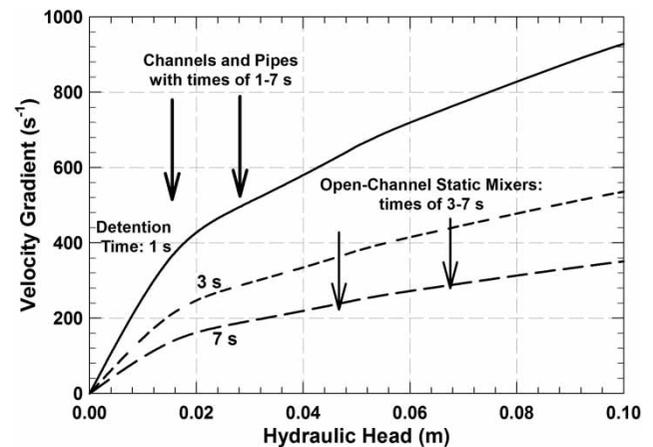


**Figure 8** | Velocity gradient ($G$) as a function of hydraulic head for plant influent channels and pipes, and open-channel static mixers (Conditions: water temperature of 15 °C; arrows show typical ranges in head loss).

and $G$ depends strongly on the time to achieve blending. If accomplished in a short time of 1–3 s by adding the coagulant before bends and turns, then $G$ values of 300–400 s$^{-1}$ can be obtained. Open-channel static mixers have detention times of several seconds. The plots show that $G$ values of about 300 s$^{-1}$ or greater are attained.

Figure 9 shows $G$ as a function of hydraulic head for weirs and for Venturi meters. With small volumes of
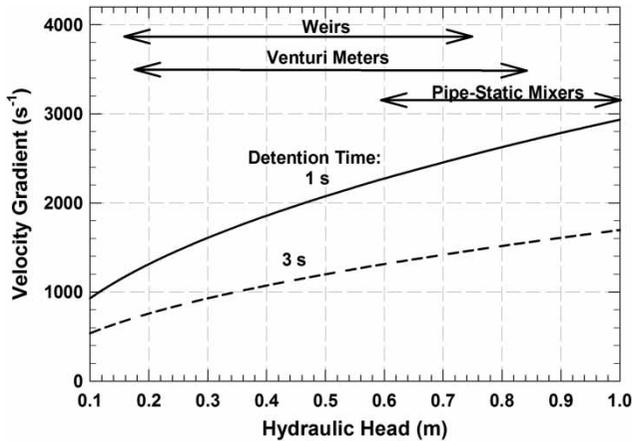
**Figure 9** │ Velocity gradient (G) as a function of hydraulic head for weirs, Venturi meters, and pipe-static mixers (Conditions: water temperature of 15 °C; arrows show typical ranges in hydraulic head; hydraulic head for Venturi meters is from the throat to the outlet where the low end is for average flow, and the high end is for maximum flow).

mixing (short detention times), these hydraulic methods produce excellent coagulant-mixing conditions and high $G$ values. Figure 9 also shows $G$ values for pipe-static mixers. High $G$ values are attained because of the high head loss and short mixing times. In most coagulation applications, which involve the mechanism of metal-coagulant precipitation, one does not require these high $G$ values. What is important is that these hydraulic methods achieve a uniform coagulant concentration, which can easily be measured at the water plant and the mixing uniformity characterized by COV as described earlier.

Hydraulic systems installed specifically for coagulant mixing such as pipe and open-channel static mixers should be sized based on the average daily flow as recommended above for rapid-mixing tanks. This practice will yield smaller units and thus a savings in capital costs. Higher flows than the average will yield higher $G$ values (not a detriment to coagulant mixing) and lower detention times which are beneficial.

## CONCLUSIONS

Several major conclusions and important applications to water treatment practice result from this paper.

1. The theory of charge-neutralization of particles leads to the concept of intense mixing requirements (high $G$) and

short mixing times. However, the application of this coagulation mechanism is limited to a small fraction of water supplies, those with low concentrations of TOC and low dissolved NOM fractions that do not complex metal coagulants. Acidic pH conditions and a low coagulant dose are required for this coagulation mechanism to avoid coagulant-metal precipitation. The main application is direct filtration for low TOC supplies.

2. Most water supplies contain both particles and dissolved NOM whereby coagulation with metals (alum, PACls, and ferric salts) involves precipitation of the coagulant-metal, what is called sweep-floc coagulation. For this coagulation mechanism, coagulation does not depend on mixing intensity. What is important are the chemical conditions affecting precipitation, these are dose (metal concentration) and pH. The goal of coagulant mixing is to achieve a uniform coagulant concentration (dose) in a short detention time or mixing volume.

3. A disadvantage of rapid-mixing tanks is that the power is applied to a relatively large volume in order to house the mechanical mixer. This is inefficient because larger volumes require more power to achieve a specified design value for $G$.

4. Coagulation is a chemical process and water plants adjust dose to the daily or hourly flow rate. The detention time and thus the size of mixing reactors installed specifically for coagulation, such as rapid-mixing tanks, pipe and static mixers, should be based on the average daily flow not the maximum daily flow.

5. For rapid-mixing tanks one can expect a considerable reduction in size, capital and energy costs. Considerable cost savings in power are realized by using low-intensity mixing and the average daily flow compared to the practice of using high-intensity mixing and the maximum daily flow. The smaller rapid-mixing tanks, lower power use, and lower power costs should be incorporated into sustainable water plant designs.

6. Hydraulic methods for coagulant addition are effective in achieving a uniform coagulant concentration in a short time within the flow undergoing treatment. These hydraulic methods include use of weirs, Venturi meters, and suction side of plant influent pumps, and by making use of turns and elbows in plant influent channels and

pipes. Open-channel static mixers are also effective and produce low head loss.

7. The hydraulic methods eliminate mixers and rapid-mixing tanks yielding savings in capital and operating costs, and a more sustainable water plant design. Hydraulic systems installed specifically for coagulant mixing, such as pipe and open-channel static mixers, should be sized based on the average daily flow yielding smaller units.

## ACKNOWLEDGMENTS

## REFERENCES

Amirtharajah, A. & Mills, K. M. 1982 Rapid-mix design for mechanisms of alum coagulation. *J. AWWA* **74** (4), 210–216.

Amirtharajah, A. & O'Melia, C. R. 1990 Coagulation processes: destabilization, mixing, and flocculation. In: *Water Quality and Treatment: A Handbook of Community Water Supplies*, 4th edn (F. W. Pontius, ed.). McGraw-Hill and AWWA, New York.

Amirtharajah, A. & Tambo, N. 1991 Mixing in water treatment. In: *Mixing in Coagulation and Flocculation* (A. Amirtharajah, M. M. Clark & R. R. Trussell, eds). American Water Works Association Research Foundation, Denver, CO.

Amirtharajah, A. & Trusler, S. L. 1986 Destabilization of particles by turbulent rapid mixing. *J. Environ. Eng.* **112**, 1085–1108.

AWWA & ASCE 2012 Chapter 7, Mixing, coagulation, and flocculation. In: *Water Treatment Plant Design*, 5th edn (S. J. Randtke & M. B. Horsley, eds). McGraw-Hill, AWWA, and ASCE, New York.

Camp, T. R. & Stein, P. C. 1943 Velocity gradients and internal work in fluid motion. *J. Boston Soc. Civil Eng.* **30**, 219–237.

Kawamura, S. 2000 *Integrated Design and Operation of Water Treatment Facilities*, 2nd edn. John Wiley & Sons, New York.

Klute, R. & Amirtharajah, A. 1991 Particle destabilization and flocculation reactions in turbulent pipe flow. In: *Mixing in Coagulation and Flocculation* (A. Amirtharajah, M. M. Clark & R. R. Trussell, eds). American Water Works Association Research Foundation, Denver, CO.

MWH 2012 *Water Treatment Design: Principles and Design*, 3rd edn (J. C. Crittenden, R. R. Trussell, D. W. Hand, D. W. Howe & G. Tchobanoglous, eds). John Wiley & Sons, Hoboken, NJ.

Pernitsky, D. J. & Edzwald, J. K. 2006 Selection of alum and polyaluminum coagulants: principles and applications. *J. Water Supply Res. Technol. Aqua* **55** (2), 121–140.

Ten State Standards of the Great Lakes-Upper Mississippi River Board of State and Provincial Public Health and Environmental Managers 2007 Recommended Standards for Water Works, Health Education Services. Albany, NY.