

**The Islamic University of Gaza
Faculty of Engineering
Civil Engineering Department**

**Environmental Engineering
(ECIV 4324)**

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Water Treatment- Part B

Coagulation and Flocculation

The most common method used to remove particles and a portion of dissolved organic matter is a combination of coagulation and flocculation followed by sedimentation and/or filtration. Coagulation is a charge neutralization step that involves the conditioning of the suspended, colloidal, and dissolved matter by adding coagulants. Flocculation involves the aggregation of destabilized particles and formation of larger particles known as floc.

PARTICLE STABILITY AND REMOVAL

Surface charge is the primary contribution to particle stability. Stable particles are likely to remain suspended in solution (and measured as turbidity or TSS). Suspended colloids and fine particles are relatively stable and cannot flocculate and settle in a reasonable period of time.

The stability of particles in natural waters primarily depends on a balance of the repulsive and attractive forces between particles. Most particles in natural waters are negatively charged, and a repulsive electrostatic force exists between particles of the same charge.

CHEMICAL COAGULANTS

A coagulant is the chemical that is added to destabilize particles and accomplish coagulation. Table provides examples of commonly used coagulants. Selection of the proper coagulant depends upon:

- (1) the characteristics of the coagulant,**
- (2) concentration and type of particulates,**
- (3) concentration and characteristics of NOM,**
- (4) Water temperature,**
- (5) water quality (for example, pH),**
- (6) cost and availability, and**
- (7) dewatering characteristics of the solids that are produced.**

CHEMICAL COAGULANTS

Table / 8.11

Types of Coagulants Commonly Used in the Field

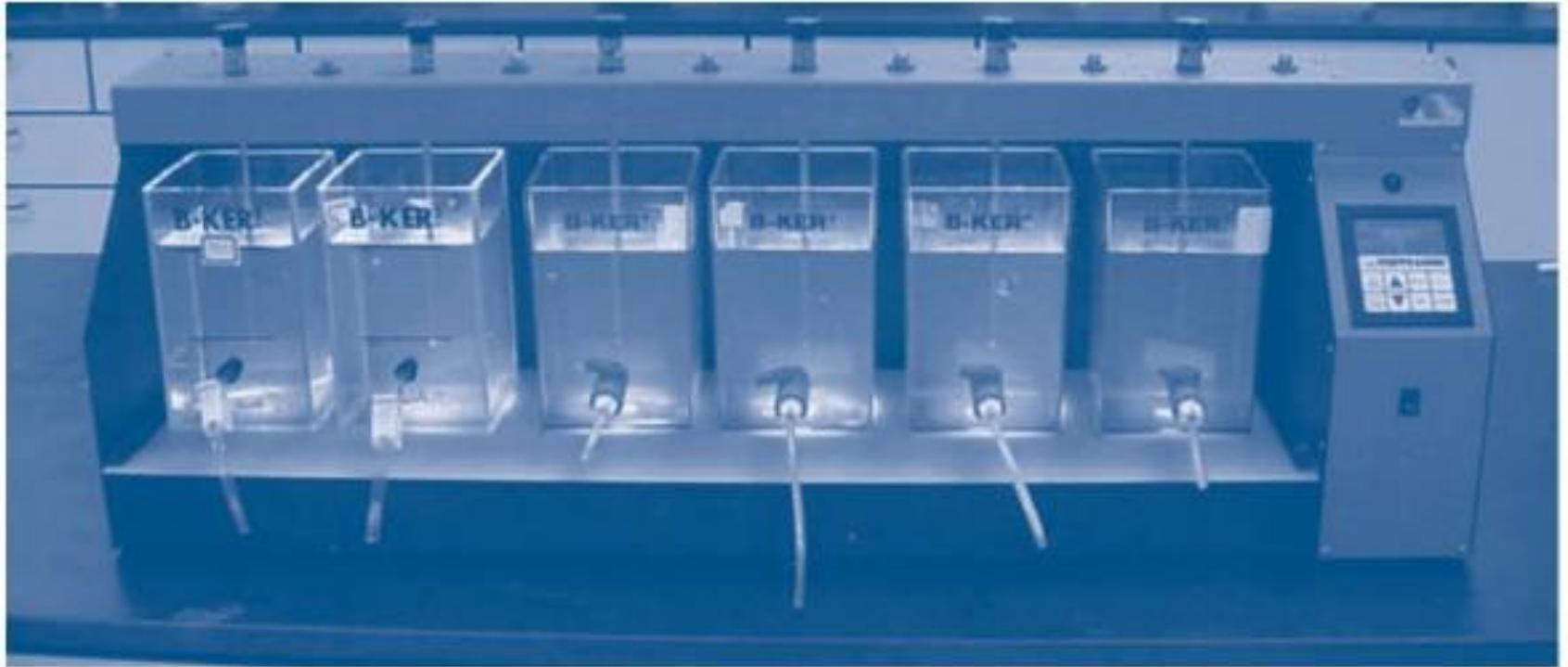
Coagulant Type	Examples
Inorganic metallic coagulants	Aluminum sulfate (also referred to as alum, $\text{Al}_2(\text{SO}_4)_3 \cdot 14\text{H}_2\text{O}$); sodium aluminate ($\text{Na}_2\text{Al}_2\text{O}_4$); aluminum chloride (AlCl_3); ferric sulfate ($\text{Fe}_2(\text{SO}_4)_3$), and ferric chloride (FeCl_3)
Prehydrolyzed metal salts	Made from alum and iron salts and hydroxide under controlled conditions; include polyaluminum chloride (PACl), polyaluminum sulfate (PAS), and polyiron chloride
Organic polymers	Cationic polymers, anionic polymers, and nonionic polymers (for synthetic polymers, molecular weight in the range of 10^4 – 10^7 g/mole)
Natural plant-based materials	<i>Opuntia</i> spp. and <i>Moringa oleifera</i> (used in many parts of the world, especially the developing world)

CHEMICAL COAGULANTS

The most commonly used coagulant is aluminum sulphate, commonly referred to as alum (molecular weight of 594 g/mole). Addition of Al_3 in the form of alum (or Fe_3 in the form of the iron salts such as ferrous sulphate ($\text{Fe}_2(\text{SO}_4)_3$) or ferric chloride, FeCl_3) at concentrations greater than their solubility limits results in the formation of the hydroxide precipitate that is typically used in the sweep floc mode of operation. The overall stoichiometric reaction for addition of alum in the formation of a hydroxide precipitate is as follows



CHEMICAL COAGULANTS



example/ 8.1 Use of Jar Testing to Determine the Optimal Coagulant Dosage

A jar test was conducted on untreated water with an initial turbidity of 10 NTU and a HCO_3^- concentration of 50 mg/L as CaCO_3 . Using the following data obtained from a jar test, estimate the optimum alum dosage for turbidity removal and the theoretical amount of alkalinity that will be consumed at the optimal dosage. Alum is added as dry alum (molecular weight of 594 g/mole).

Alum dose, mg/L	5	10	15	20	25	30
Turbidity, NTU	8	6	4.5	3.5	5	7

solution

The data are graphed as shown in Figure 8.6. The graph shows that the turbidity reaches the lowest value when the alum dose is 20 mg/L. This is the optimum alum dosage.

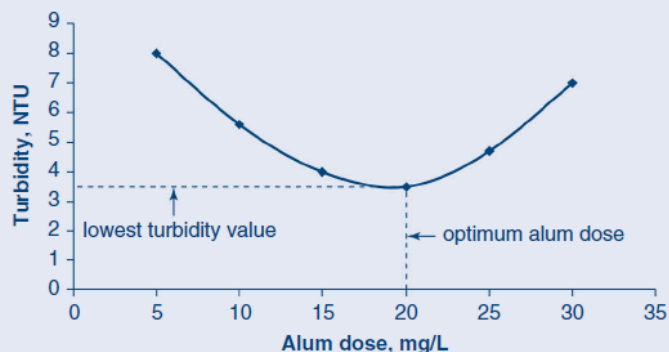


Figure / 8.6 Jar Test Results That Will Aid Identification of Proper Coagulant Dosage.

Next, we must determine the amount of alkalinity consumed and check this value against the naturally occurring alkalinity to determine whether additional alkalinity needs to be added. Use the stoichiometry of Equation 8.1 to determine the alkalinity consumed:

$$\begin{aligned}\text{alkalinity consumed} &= (20 \text{ mg/L Al}_2(\text{SO}_4)_3 \cdot 14\text{H}_2\text{O}) \times \left(\frac{1\text{g}}{1,000 \text{ mg}} \right) \\ &\times \left(\frac{1 \text{ mole/L Al}_2(\text{SO}_4)_3 \cdot 14\text{H}_2\text{O}}{594 \text{ g/mole Al}_2(\text{SO}_4)_3 \cdot 14\text{H}_2\text{O}} \right) \times \left(\frac{6 \text{ mole HCO}_3^-}{1 \text{ mole Al}_2(\text{SO}_4)_3 \cdot 14\text{H}_2\text{O}} \right) \\ &\times \left(\frac{1 \text{ eqv alkalinity}}{1 \text{ mole HCO}_3^-} \right) \times \left(\frac{100 \text{ g CaCO}_3}{2 \text{ eqv alkalinity}} \right) \\ &= 0.01 \text{ g/L as CaCO}_3 = 10 \text{ mg/L as CaCO}_3\end{aligned}$$

Thus, 10 mg/L of alkalinity as CaCO_3 are consumed, and the water sample had an initial alkalinity of 50 mg/L as CaCO_3 . Therefore, the alkalinity in the raw water is sufficient to buffer the acidity produced after alum addition.

OTHER CONSIDERATIONS

Rapid-mixing systems and most flocculation units operate under turbulent mixing conditions. Under these conditions, velocity gradients are not well defined, and the root mean square (RMS) velocity gradient has been widely adopted for assessing energy input

$$\overline{G} = \sqrt{\frac{P}{\mu V}}$$

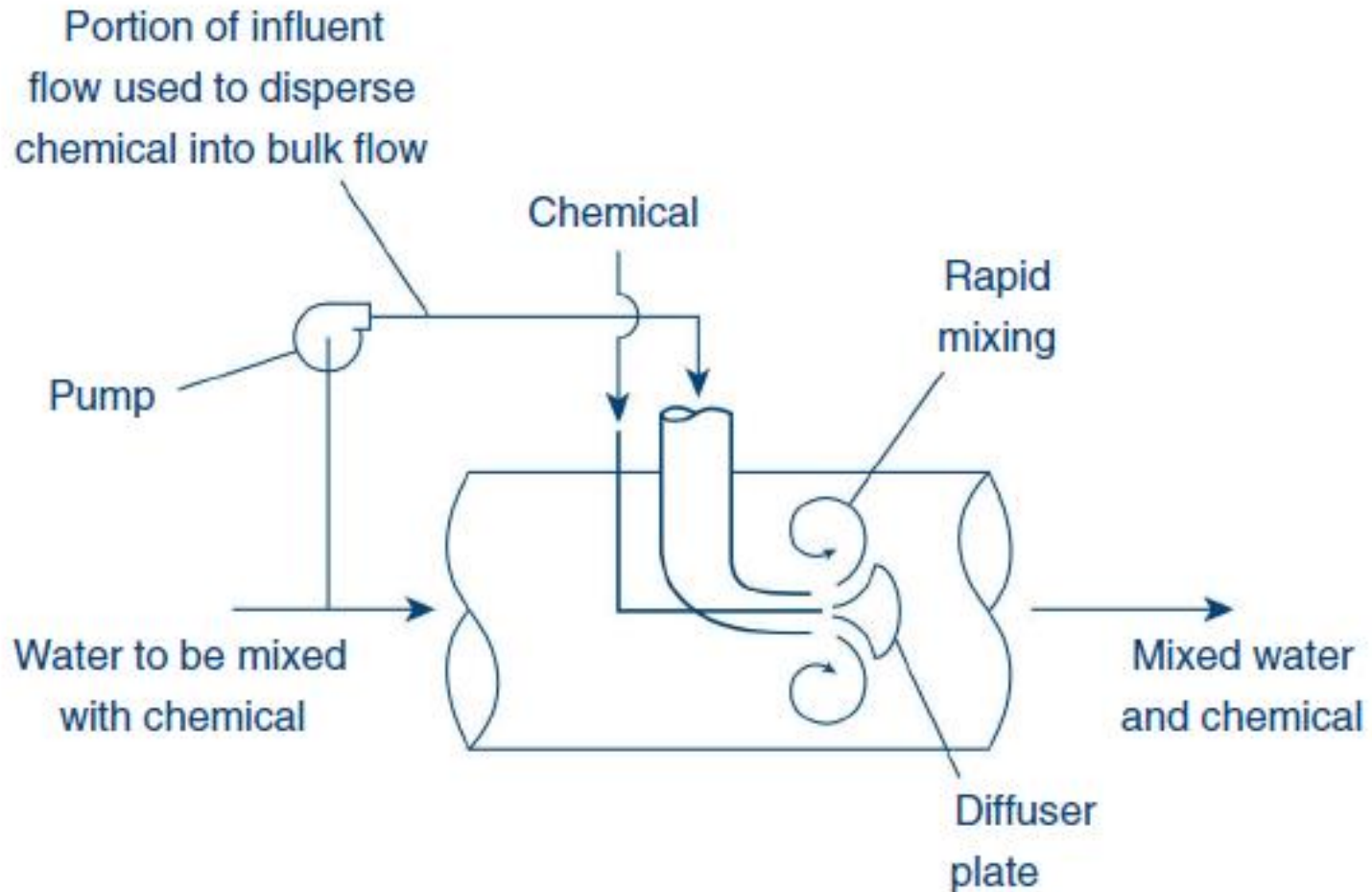
OTHER CONSIDERATIONS

Table / 8.12

Typical Values Used in Design of Rapid-Mixing and Flocculation Systems

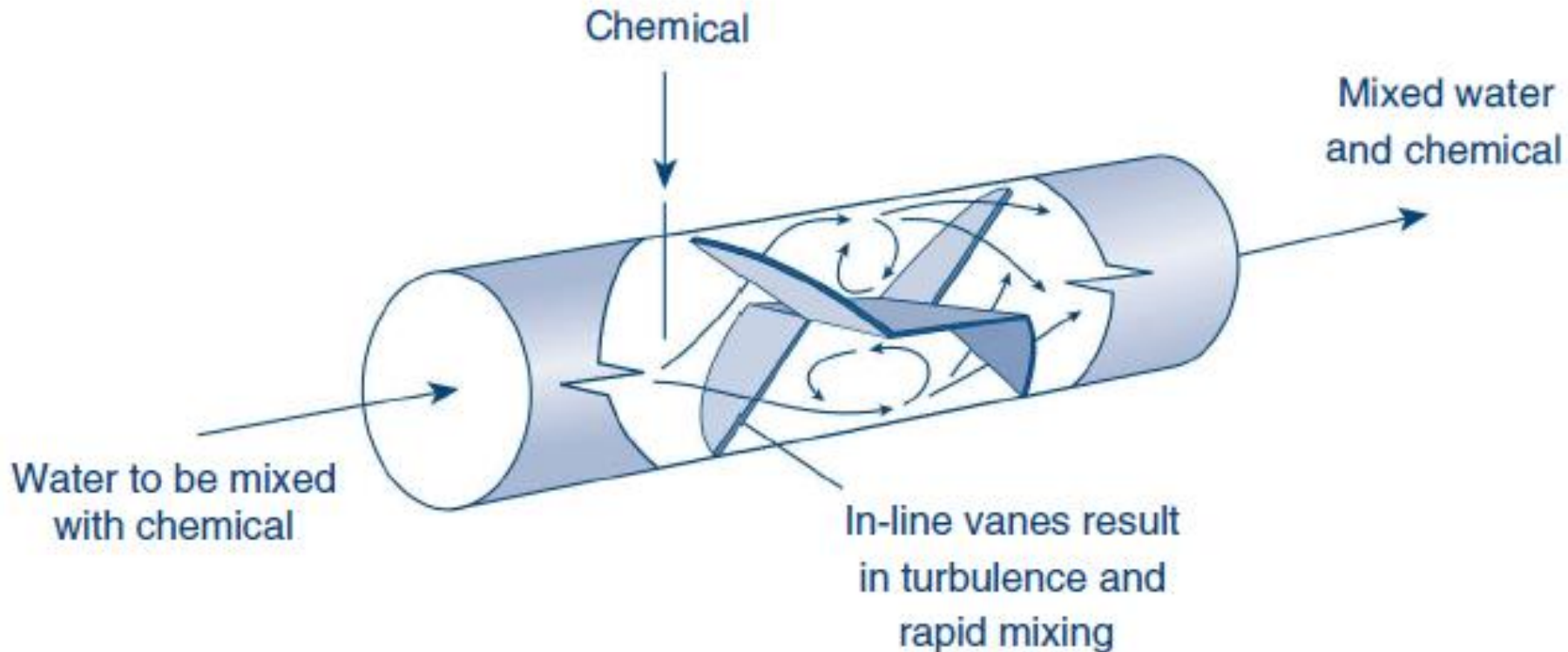
System Category	RMS Velocity Gradient, $\bar{G}$ (s^{-1})	Detention Time, t	$\bar{G}t$ Values
Mechanical mixing	600–1,000	10–120 s	5.0×10^4 to 5.0×10^5
In-line mixing	3,000–5,000	1 s	1.0×10^3 to 1.0×10^5
Horizontal-shaft paddle flocculator	20–50	10–30 min	1.0×10^4 to 1.0×10^5
Vertical-shaft turbine flocculator	10–50	10–30 min	1.0×10^4 to 1.0×10^5

Rapid-Mixing Approaches Used to Disperse a Chemical Coagulant



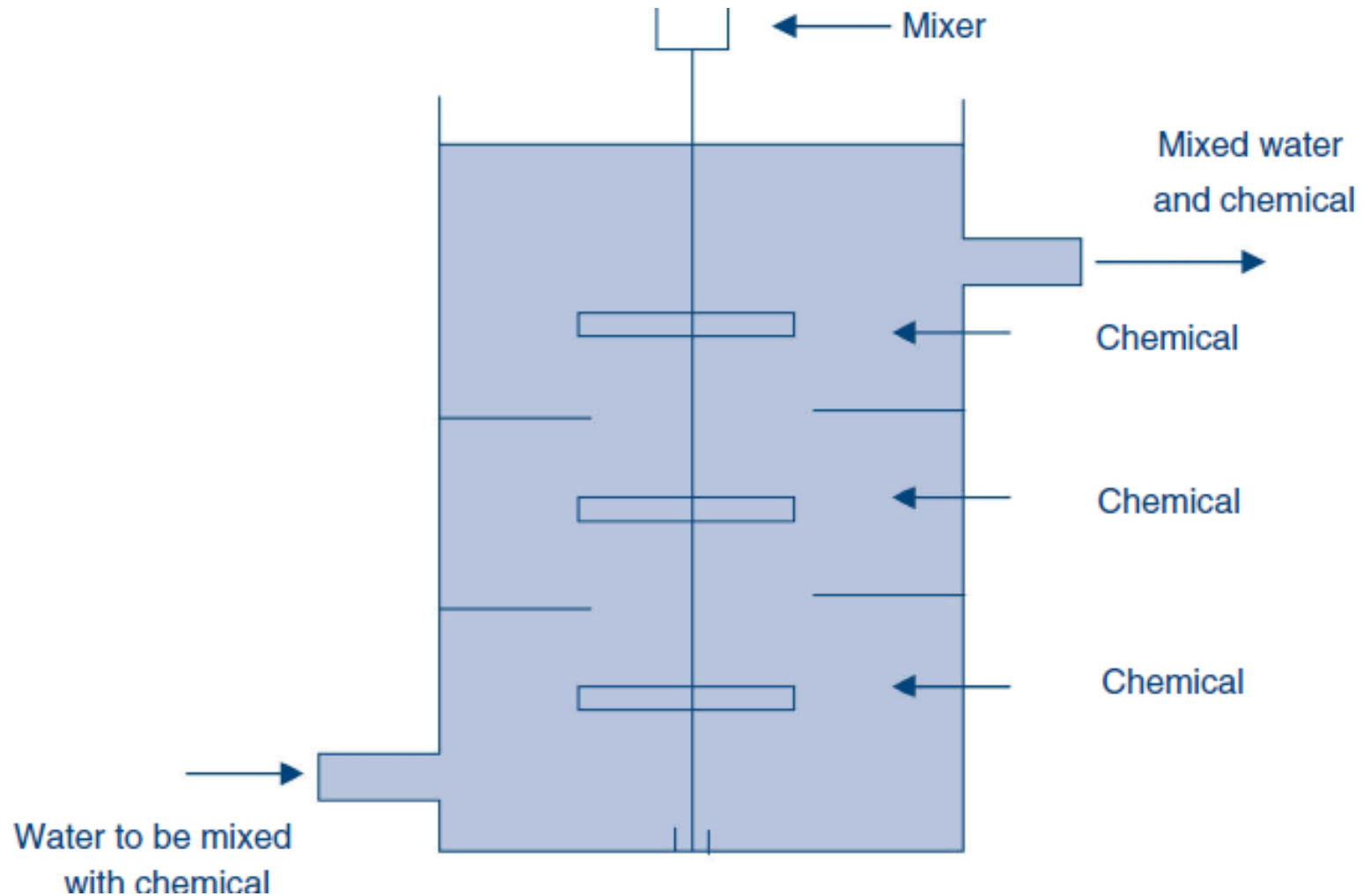
pumped flash mixing

Rapid-Mixing Approaches Used to Disperse a Chemical Coagulant



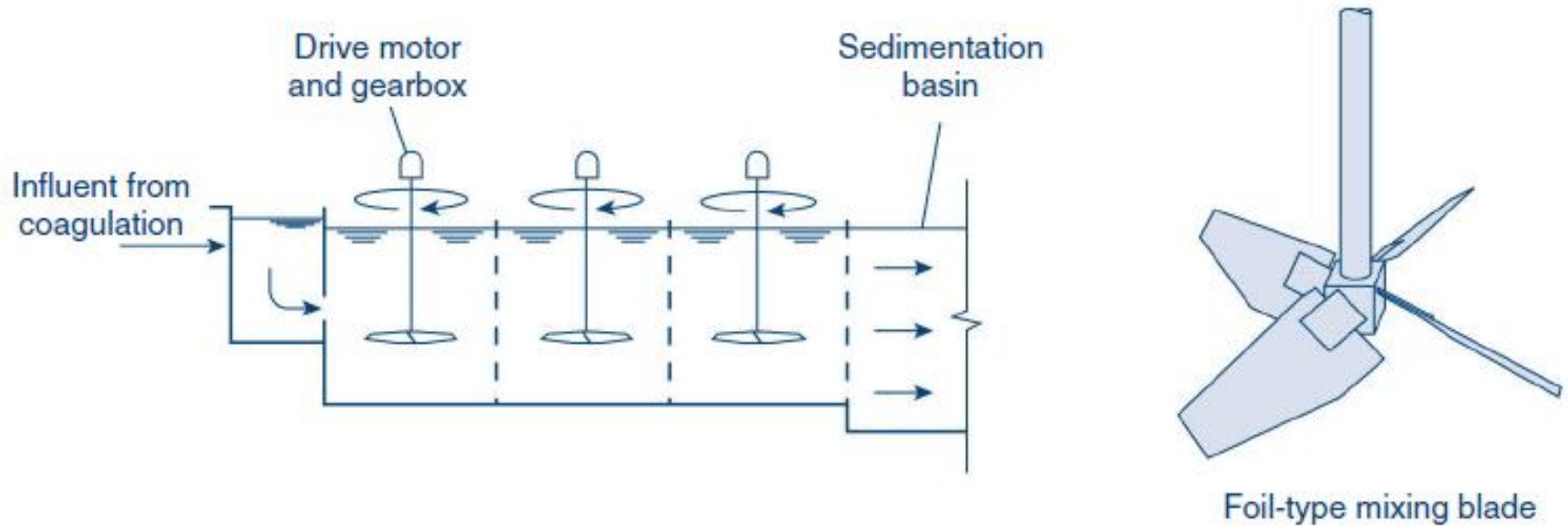
in-line static mixer

Rapid-Mixing Approaches Used to Disperse a Chemical Coagulant



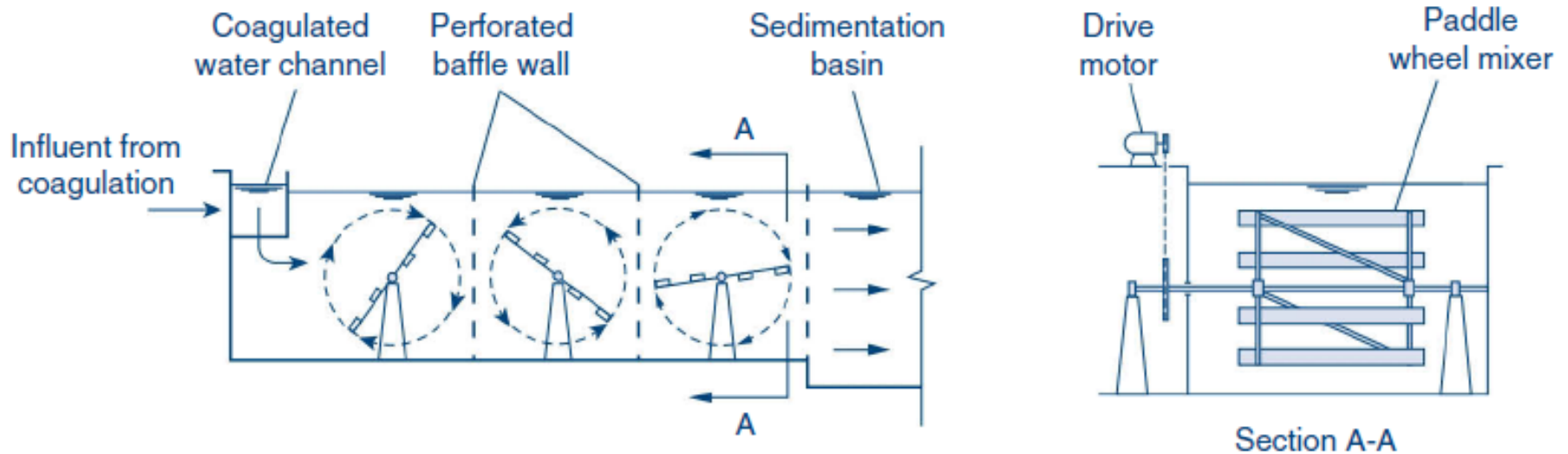
conventional stirred tank

Common Types of Gentle Mixing Employed in Flocculation Systems



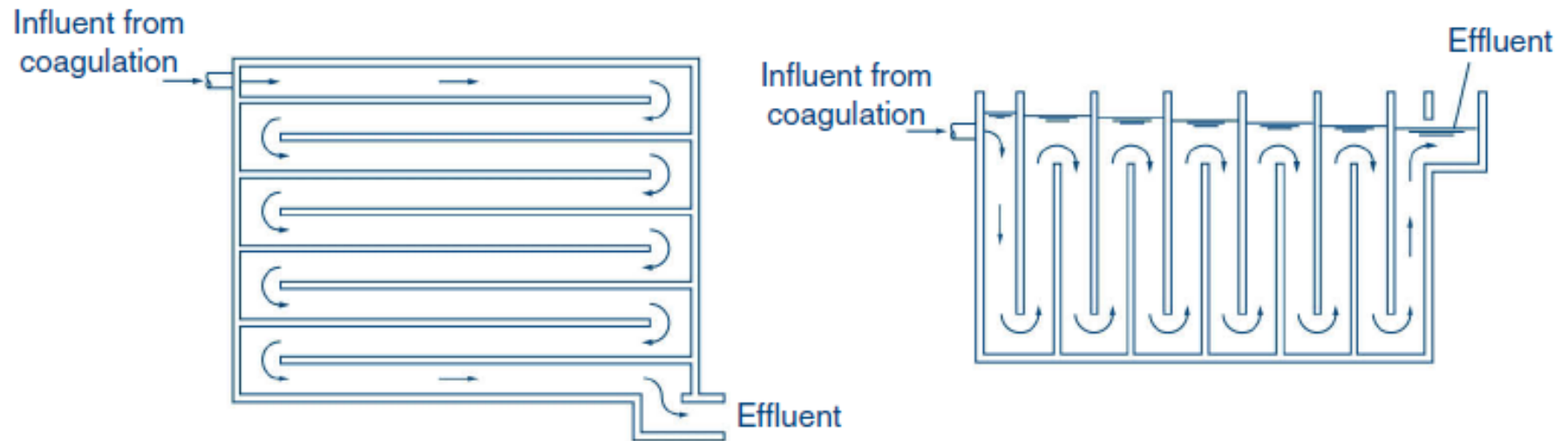
a vertical-shaft turbine flocculation system

Common Types of Gentle Mixing Employed in Flocculation Systems



a horizontal-shaft paddle wheel flocculation system

Common Types of Gentle Mixing Employed in Flocculation Systems



a hydraulic flocculation system

example/ 8.2 Design of a Mechanical Rapid-Mix Tank

A conventional stirred tank is used for rapid mixing in a water treatment plant with a flow of 100×10^6 L/day. The water temperature is 10°C . Determine the tank volume and power requirement.

solution

The tank volume equals the flow rate (Q) times the hydraulic detention time (θ). Table 8.12 provides appropriate detention times. Conventional stirred tanks are considered a form of mechanical mixing, and we will select a detention time value of 60 s:

$$V = Q \times \theta = \frac{100 \times 10^6 \text{ L}}{\text{day}} \times 60 \text{ s} \times \frac{1 \text{ min}}{60 \text{ s}} \times \frac{1 \text{ day}}{1,440 \text{ min}} \times \frac{\text{m}^3}{1,000 \text{ L}} = 69 \text{ m}^3$$

To determine the power requirement, use Table 8.12 to select an appropriate RMS velocity gradient. Here we will select a $\bar{G}$ value of $900/\text{s}$, and the product of $\bar{G}$ and t ($900/\text{s} \times 60 \text{ s} = 5.4 \times 10^4$) is within the range (5×10^4 to 5×10^5) provided in Table 8.12. At 10°C , $\mu = 0.001307 \text{ N}\cdot\text{s}/\text{m}^2$. To obtain power consumption, rearrange Equation 8.2 to solve for P :

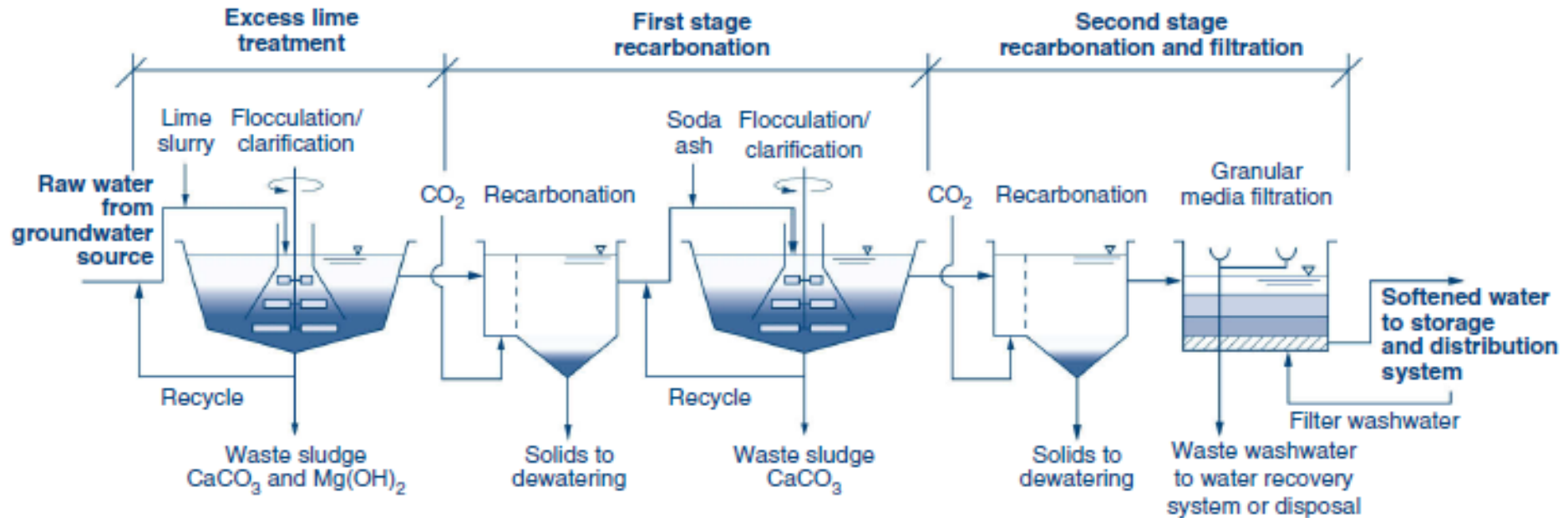
$$\begin{aligned} P &= \bar{G}^2 \times \mu \times V = (900/\text{s})^2 \times 0.001307 \frac{\text{N}\cdot\text{s}}{\text{m}^2} \times 69 \text{ m}^3 \times \frac{1 \text{ kN}}{1,000 \text{ N}} \\ &= 73 \frac{\text{kN} \cdot \text{m}}{\text{s}} = 73 \text{ kW} \end{aligned}$$

Hardness Removal

Water hardness is caused by divalent cations, primarily calcium and magnesium ions (Ca^{+2} and Mg^{+2}). When Ca^{+2} and Mg^{+2} are associated with alkalinity anions (for example, HCO_3^-), the hardness is defined as carbonate hardness. The term noncarbonated hardness is used if the Ca^{+2} and Mg^{+2} are associated with non alkalinity anions (for example, SO_4^{-2})



Hardness Removal

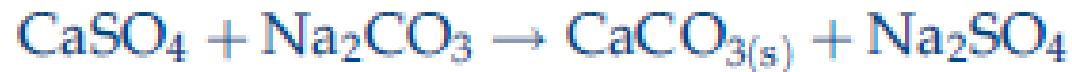
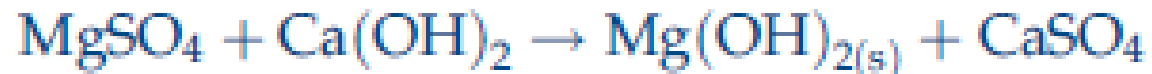


Hardness Removal

Carbonate hardness removal is given by



Noncarbonate hardness removal is given by



Hardness Removal

example/ 8.3 Lime-Soda Ash Softening

A groundwater contains the following constituents: $\text{H}_2\text{CO}_3^* = 62\text{mg/L}$, $\text{Ca}^{2+} = 80\text{mg/L}$, $\text{Mg}^{2+} = 36.6\text{mg/L}$, $\text{Na}^+ = 23\text{mg/L}$, alkalinity (HCO_3^-) = 250mg/L as CaCO_3 , $\text{SO}_4^{2-} = 96\text{mg/L}$, and $\text{Cl}^- = 35\text{mg/L}$. The facility is to treat $50 \times 10^6\text{L/day}$ (15 MGD) of water from this source using lime-soda ash to reduce the hardness.

1. Determine the total, carbonate, and noncarbonated hardness present in the raw water.
2. Determine the lime and soda ash dosages for softening (units of kg/day). Assume the lime is 90 percent CaO by weight and the soda ash is pure sodium carbonate.

solution

This problem requires several steps. First construct a table of the chemical constituents and their concentrations in terms of mg/L as CaCO_3 (see Table 8.14).

The second step determines the total hardness, carbonate hardness, and noncarbonate hardness. The total hardness is the sum of the calcium and magnesium ions as CaCO_3 :

$$\text{total hardness} = (200 + 150) = 350 \text{ mg/L as CaCO}_3$$

The carbonate hardness is the sum of the calcium and magnesium ions associated with bicarbonate ions. Because the total hardness (350 mg/L as CaCO_3) is greater than bicarbonate alkalinity (250 mg/L CaCO_3), all the bicarbonate is associated with calcium (200 mg/L CaCO_3) and magnesium (50 mg/L CaCO_3). The carbonate hardness is thus equal to bicarbonate alkalinity as CaCO_3 :

$$\text{carbonate hardness} = 200 + 50 = 250 \text{ mg/L as CaCO}_3$$

The noncarbonate hardness equals the magnesium ions not associated with carbonate hardness (MgSO_4):

$$\text{noncarbonate hardness} = (150 - 50) = 100 \text{ mg/L as CaCO}_3$$

Hardness Removal

example/ 8.3 (continued)

The second question requests we determine the daily mass of lime and soda ash required for softening. The lime that is required will react with CO_2 (H_2CO_3^*), $\text{Ca}(\text{HCO}_3)_2$, $\text{Mg}(\text{HCO}_3)_2$, and MgSO_4 . The stoichiometric amount of $\text{Ca}(\text{OH})_2$ can be calculated based on Equations 8.3–8.6.

$\text{Ca}(\text{OH})_2$ required to react with $\text{CO}_2 = 100 \text{ mg/L as CaCO}_3$

$\text{Ca}(\text{OH})_2$ required to react with $\text{Ca}(\text{HCO}_3)_2 = 200 \text{ mg/L as CaCO}_3$

$\text{Ca}(\text{OH})_2$ required to react with $\text{Mg}(\text{HCO}_3)_2 = 2 \times \text{Mg}(\text{HCO}_3)_2 = 2 \times 50 = 100 \text{ mg/L as CaCO}_3$

$\text{Ca}(\text{OH})_2$ required to react with $\text{MgSO}_4 = 100 \text{ mg/L as CaCO}_3$

Remember that 30–70 mg/L of extra lime must be added to raise the pH above 10.5 to ensure that magnesium is removed as $\text{Mg}(\text{OH})_2$. Assume 30 mg/L (as CaCO_3) of additional lime is required in the process.

The total lime requirement is thus determined from the summation of all five individual lime requirements:

$$\begin{aligned} \text{lime required} &= \left(\frac{100 \text{ mg CaCO}_3}{\text{L}} + \frac{200 \text{ mg CaCO}_3}{\text{L}} + \frac{100 \text{ mg CaCO}_3}{\text{L}} + \frac{100 \text{ mg CaCO}_3}{\text{L}} + \frac{30 \text{ mg CaCO}_3}{\text{L}} \right) \\ &\quad \times \frac{56 \text{ mg CaO/mmole}}{100 \text{ mg CaCO}_3/\text{mmole}} \times \frac{\text{kg}}{10^6 \text{ mg}} \times \frac{50 \times 10^6 \text{ L}}{\text{day}} \times \frac{\text{kg bulk lime}}{0.9 \text{ kg CaO}} \\ &= 16,500 \text{ kg/day} \end{aligned}$$

The soda ash (Na_2CO_3) required is also determined by reaction stoichiometry:

soda ash = noncarbonate hardness

$$= 100 \text{ mg CaCO}_3/\text{L} \times \frac{106 \text{ mg Na}_2\text{CO}_3/\text{mmole}}{100 \text{ mg CaCO}_3/\text{mmole}} \times \frac{\text{kg}}{10^6 \text{ mg}} \times \frac{50 \times 10^6 \text{ L}}{\text{day}} = 5,300 \text{ kg/day}$$

Hardness Removal

Table Constructed to Solve Example 8.3

Chemical Constituent	Concentration (mg/L)	Equivalents/mole	Molecular Weight (g/mole)	Equivalent Weight (g/eqv)	Concentration (meqv/L)	Concentration (mg/L as CaCO ₃)
H ₂ CO ₃ *	62	2	62.0	31.0	2.0	100
<i>Cations</i>						
Ca ²⁺	80	2	40.0	20.0	4.0	200
Mg ²⁺	36.6	2	24.4	12.2	3.0	150
Na ⁺	23.0	1	23.0	23.0	1.0	50
				Total	9.0	400
<i>Anions</i>						
Alk (HCO ₃ ⁻)	250.0	2	100.0	50.0	5.0	250
SO ₄ ²⁻	96.0	2	96.0	48.0	2.0	100
Cl ⁻	35	1	35.5	35.5	1.0	50
				Total	9.0	400