CHAPTER 13

COAGULATION AND FLOCCULATION

13.1 COAGULATION

Coagulation is the destabilization of colloidal particles. The particles are essentially coated with a chemically sticky layer that allows them to flocculate (agglomerate) and settle in a reasonable period of time. Coagulation of waters to aid their clarification has been practiced since ancient times (Baker, 1981). Many naturally occurring compounds from starch to iron and aluminum salts can accomplish coagulation. In addition, synthetic cationic, anionic, and nonionic polymers are very effective coagulants but are usually more costly than natural compounds.

Coagulation and flocculation are used in both water and wastewater treatment processes. In water treatment it is usually cost effective to apply coagulation and flocculation to remove colloidal and small particles that settle slowly. Coagulation–flocculation can also be applied to enhance the removal of solids in highly concentrated natural waters that contain significant amounts of settleable solids (Guibai and Gregory, 1991). Commonly, presedimentation without coagulant addition or a roughing filter is used to remove high concentrations of settleable solids before coagulation–flocculation–sedimentation.

Biological wastewater treatment processes produce microorganisms that naturally flocculate themselves and other suspended matter, although it may be necessary to add coagulating agents to assist their flocculation in times of poor performance. Coagulants may also be added continuously for nutrient removal. Physical–chemical wastewater treatment processes rely on coagulation–flocculation for removal of suspended matter.

The ability of an agent to coagulate a water is related to its charge. The size of synthetic polymers is also a factor. Table 13.1 lists the relative coagulating power of several common salts. There is more than an order of magnitude increase in the effectiveness of an ion as its charge increases by one. This is a statement of the Schultze–Hardy rule based on the work of these two researchers in 1882 and 1900, respectively.

The most common coagulants are alum (aluminum sulfate) and iron salts, with alum being the most extensively used agent. The multivalent characteristic of these cations strongly attracts them to charged colloidal particles and their relative insolubility ensures their removal to a high degree.

Typical reactions of aluminum and iron salts in water are shown in Table 13.2. These salts consume alkalinity, which may necessitate the addition of an alkaline agent. Lime is usually the least expensive source of alkalinity. The pH of coagulation is critical. Ferric salts work best in a pH range of 4.5–5.5, whereas aluminum salts are most effective around a pH range of 5.5–6.3. These pH values should be attained

TABLE 13.1 Coagulating Power of Inorganic Electrolytes

	Relative power of coagulation	
Electrolyte	Positive colloids	Negative colloids
NaCl	1	1
Na_2SO_4	30	1
Na_3PO_4	1 000	1
$BaCl_2$	1	30
$MgSO_4$	30	30
$AlCl_3$	1	1 000
$Al_2(SO_4)_3$[a]	30	>1 000
$FeCl_3$	1	1 000
$Fe_2(SO_4)_3$[a]	30	>1 000

[a]The most common coagulating agents.

after the coagulant is added. If necessary, the pH may be adjusted with acid or alkalinity. Note that alum and some iron salts are supplied in hydrated states. Dry alum is hydrated with 14.3–18 water molecules [$Al_2(SO_4)_3 \cdot 14.3H_2O$ or $Al_2(SO_4)_3 \cdot 18H_2O$]. Table A.3 in the Appendix gives concentrations of commercially available coagulating agents.

Temperature exerts an effect on the efficiency of coagulation and flocculation. Metal salts given in Table 13.2 form hydroxide precipitates, which logically leads to the supposition that pOH is an important factor in the chemistry of the process. Temperature affects the equilibrium constant of water, as discussed in Section 3.1;

TABLE 13.2 Chemistry of Aluminum, Iron Salts, and Lime Coagulation

1. Alum

$Al_2(SO_4)_3 \cdot 18H_2O + 6H_2O \rightarrow 2Al(OH)_3(s) + 6H^+ + 3SO_4^{2-} + 18H_2O$

With an increase in H^+, pH is depressed and no more $Al(OH)_3$ is formed. If natural alkalinity is present, then

$HCO_3^- + H^+ \rightleftharpoons H_2CO_3 \rightleftharpoons CO_2 + H_2O$

$Al_2(SO_4)_3 \cdot 18H_2O + 3Ca(HCO_3)_2 \rightarrow 2Al(OH)_3(s) + 3CaSO_4 + 6CO_2 + 18H_2O$

If natural alkalinity is insufficient, then lime or caustic soda can be added.

$AL_2(SO_4)_3 \cdot 18H_2O + 3Ca(OH)_2 \rightarrow 2Al(OH)_3(s) + 3CaSO_4 + 18H_2O$

2. Sodium Aluminate

$Na_2Al_2O_4 + Ca(HCO_3)_2 + 2H_2O \rightarrow Al(OH)_3(s) + CaCO_3(s) + Na_2CO_3$

3. Ferrous Sulfate

$FeSO_4 \cdot 7H_2O + Ca(OH)_2 \rightarrow Fe(OH)_2 + CaSO_4 + 7H_2O$

$4Fe(OH)_2 + O_2 + 2H_2O \rightarrow 4Fe(OH)_3(s)$

4. Chlorinated Copperas

$3FeSO_4 \cdot 7H_2O + 1.5Cl_2 \rightarrow Fe_2(SO_4)_3 + FeCl_3 + 21H_2O$

$2FeCl_3 + 3Ca(HCO_3)_2 \rightarrow 2Fe(OH)_3(s) + 3CaCl_2 + 7CO_2$

This reaction takes place if natural alkalinity is present in a sufficient amount. Otherwise, if lime is added,

$2FeCl_3 + 3Ca(OH)_2 \rightarrow 2Fe(OH)_3(s) + 3CaCl_2$

5. Ferric Sulfate

$Fe_2(SO_4)_3 + 3Ca(HCO_3)_2 \rightarrow 2Fe(OH)_3(s) + 3CaSO_4 + 6CO_2$

$Fe_2(SO_4)_3 + 3Ca(OH)_2 \rightarrow 2Fe(OH)_3(s) + 3CaSO_4$

therefore, maintaining the same pH at all temperatures will result in varying pOHs. For both iron and alum salts, Hanson and Cleasby (1990) found that a constant pOH over the temperature range of 5–20°C produced the best coagulation–flocculation results.

The association of aluminum with Alzheimer's disease was discussed in Chapter 8. Use of aluminum salts as coagulants may increase the concentration of Al in product water. Letterman and Driscoll (1988) surveyed 91 plants in North America that use alum and found that 75% of the plants produced water with 210 μg/L or less total Al; the 50th percentile value was 90 μg/L. The results of their survey were in good agreement with an earlier survey (Miller et al., 1984). High raw water Al concentrations were associated with higher residual Al concentrations. Effective removal of particulate matter by filtration minimizes residual Al concentrations. Letterman and Driscoll's study found that lime used for pH adjustment after filtration may be an important source of residual Al in product water.

For in-line filtration of cold waters (temperature <3°C) with turbidities less than 2 nephlometric turbidity units (NTU), ferric chloride removed turbidity more effectively than alum on a mole to mole of metal ion basis (Haarhoff and Cleasby, 1988) but alum caused slower head loss development.

Metal precipitates are often colloidal. Conventional treatment of metal finishing wastes involves the addition of base to precipitate metals as hydroxides. Coagulants such as iron salts are often added to improve solids/liquid separation, with further benefits of contaminant adsorption onto iron hydroxide. The benefits of iron hydroxide are directly related to its concentration (Edwards and Benjamin, 1989). In general, Edwards and Benjamin (1989) found that iron hydroxide removed an equal or greater percentage of soluble Cu, Cd, Zn, Cr(III), Ni, and Pb from a waste at all pHs than base addition to form metal hydroxide precipitates. Cr(VI) was not removed in the presence or absence of iron. A pH range of 8–12.5 resulted in removals >98% of all metals [except Cr(VI)] in the presence of iron hydroxide.

Synthetic coagulating agents are widely available. Cationic, anionic, and nonionic polymers have all been found to provide excellent results in different situations. These agents are usually more costly than alum or iron salts but much smaller dosages are required. Polymers do not produce voluminous, gelatinous flocs as their inorganic counterparts do.

Figure 13.1 gives general formulas of synthetic polymers. Nonionic polymers are almost exclusively polyacrylamides with a molar mass between 1 and 30 million. Anionic polyelectrolytes have masses of several million. They contain groups that permit absorption and negatively ionized groups (carboxyl or sulfuric groups), which extend the polymer. Soda ash (Na_2CO_3) has been used to partially hydrolyze the polyacrylamide groups in the figure. Cationic polymers have molar masses less than one million. Their chains have amine, imine, or quaternary ammonium groups that produce the positive charge.

Activated silica is another commonly used coagulation agent. Sodium silicate (Na_2SiO_3) is "activated" by acidification. The chemistry of activated silica is fairly complex but Stumm et al. (1967) have provided the basic explanation of the process. When a concentrated solution of sodium silicate is acidified it becomes over saturated with respect to the precipitation of SiO_2. The precipitation process begins with the formation of polysilicate polymers that contain $-Si-O-Si-$ linkages. These polysilicates react further by cross-linking and aggregation to form negatively charged silica sols. The solution contains anionic polysilicates and other silicate species, which are effective coagulants. Over time, SiO_2 will precipitate and the solution will lose much

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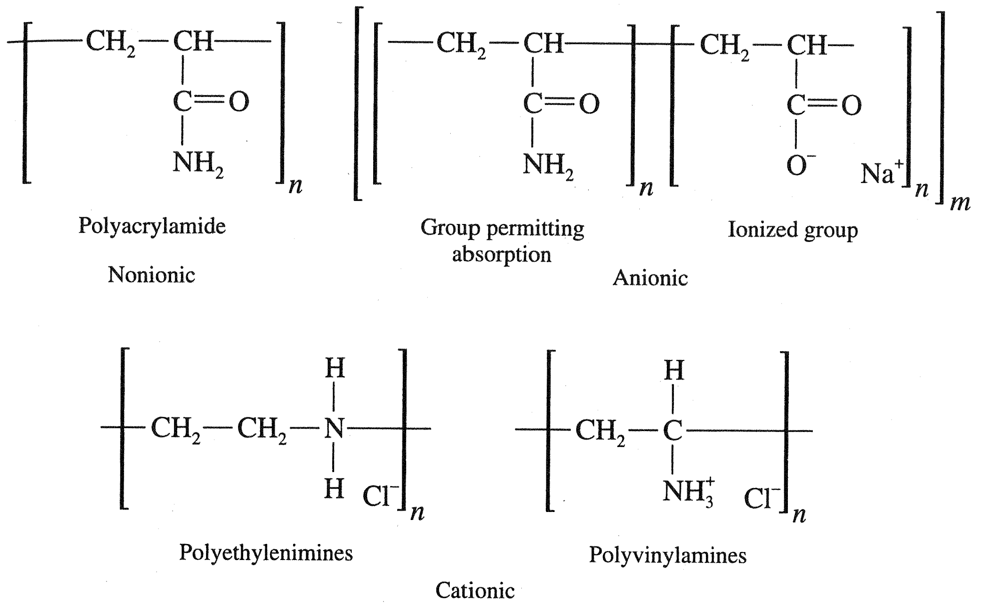

Figure 13.1 Typical formulas of coagulant polymers. After Degrémont Infilco (1979).

of its coagulating strength. Although the acidified solution is thermodynamically unstable, it can remain active for periods up to a few weeks.

Ozone has been found to be an effective coagulant aid (Singer, 1990). Low dosages (<3 mg/L and often 0.5–1.5 mg/L) are most effective and overdosing can actually deteriorate coagulation. Ozone does not improve ultimate particle removal but it facilitates the removal of readily coagulatable material with greater economy of coagulant (Singer, 1990).

There are also natural polyelectrolytes that are effective coagulant aids. Extracts from seeds, leaves, and roots have been used for centuries in the far east to clarify waters. Chitosan is a cationic polymer (molecular weight approximately 10^6) made by acidifying chitin, which is the organic skeletal substance of shells of crustaceans such as lobsters, shrimp, and crabs. Chitosan is biodegradable and nontoxic. Feed solutions of chitosan must have a pH below 6.5 (Kawamura, 1991a). Doses of 0.2 mg/L improved flocculation with alum significantly and reduced the alum dose.

Sodium alginate is an extract from certain brown seaweeds (kelp) and is widely used in foods. Sodium alginate in doses less than 1.0 mg/L also improved coagulation with alum (Kawamura, 1991a). The preparation and application of these and other natural agents are described by Schulz and Okun (1984).

The effectiveness and required doses of coagulants for a water are evaluated by use of a jar testing machine (Fig. 13.2). The apparatus is operated to simulate a mixing, flocculation, and settling cycle. Varying amounts of coagulants, alkalinity agents, and coagulant aids are added at the same time to the jars that contain the water to be treated. To ensure that the coagulants are added at the same time to all of the beakers, an arm with six test tubes attached and spaced at the separation distance of the beakers should be used to add the coagulants. The jars are then mixed at high speed for a short period of time, around 1 min. This rapid mixing phase is followed by a 20- to 40-min period of gentle mixing to promote formation of flocs. Mixing is then terminated and the impellers are withdrawn from the jars. The suspension is allowed to settle for a period of 15–60 min. Comparisons of initial and final turbidities determine the

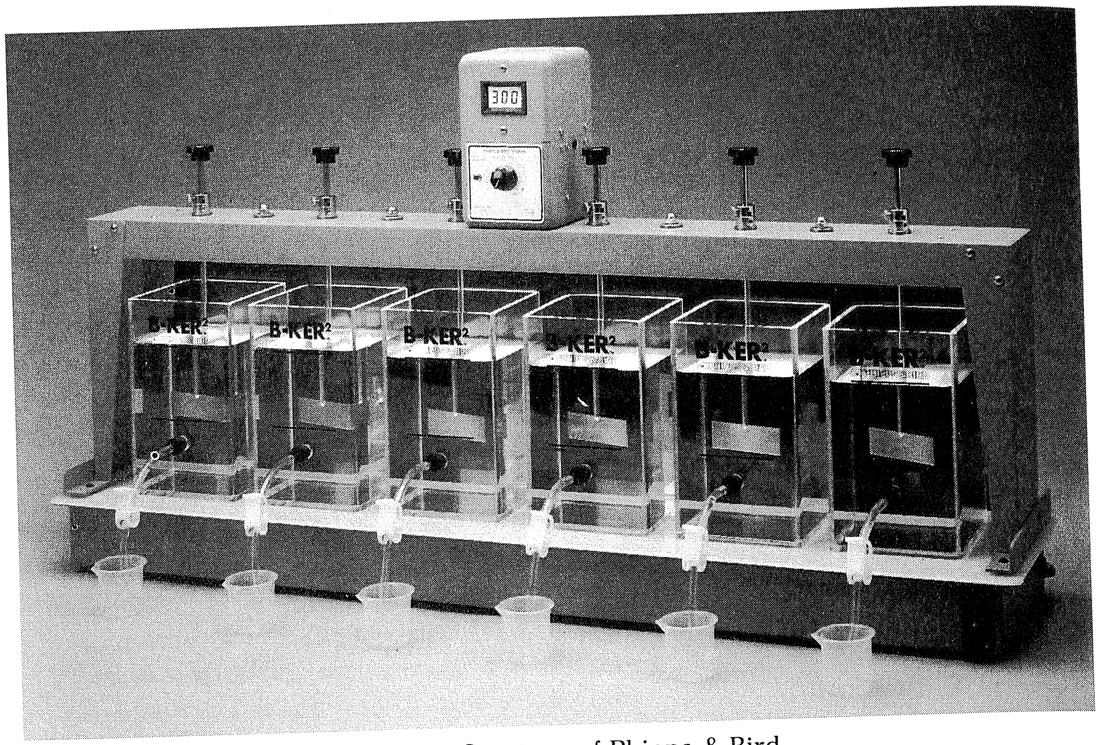

Figure 13.2 Jar testing apparatus. Courtesy of Phipps & Bird.

choice and effective doses of reagents and other conditions such as alkalinity and pH requirements. Cost and other considerations such as delivery systems determine the coagulant to be used.

Coagulants may be fed in dry or liquid form (see Table A.3 in the Appendix). Metering pumps used to deliver liquid agents can usually be varied over a 1:10 flow rate to accommodate variable doses. Manufacturers specify other requirements of chemical feed systems.

Recovery of Alum and Iron Coagulants

Alum and iron salts may be recovered from sludge by adding acid. If sulfuric acid is used,

$$\mathrm{Me(OH)}_x + x\mathrm{H}^+ + \frac{x}{2}\mathrm{SO}_4^{2-} \rightarrow \mathrm{Me(SO}_4)_{x/2} + x\mathrm{H}_2\mathrm{O} \qquad (13.1)$$

Other metals will be solubilized along with the coagulant metal. Reuse of the recovered coagulant will recycle metals that should again be precipitated along with the coagulant. The increased risk associated with acid coagulant recovery has decreased the frequency of this practice. Careful monitoring is required to ensure that product water does not exhibit elevated metals concentrations when coagulant recovery and reuse is practiced.

Iron hydroxide metals containing sludge was able to be regenerated at least 50 times by addition of acid regeneration solution with a pH of 3.5 or 4.5 (Edwards and Benjamin, 1989). After the sludge was exposed to the regeneration solution for 10 to 30 min, the remaining iron solids were separated and reused to treat waste. Addition of acid released the removed metals from the iron hydroxide sludge.

13.2 MIXING AND POWER DISSIPATION

Coagulants and coagulant aids must be rapidly dispersed throughout a water to ensure maximum contact between the reagent and suspended particles; otherwise, the coagulant will react with water and dissipate some of its coagulating power. Mixers are also required to disperse other chemical agents in waters or wastewaters. Flocculators operate at lower degrees of mixing to promote particle contact but prevent breakup of the large floc particles formed.

Three phenomena contribute to mixing: molecular diffusion (perikinetic motion), eddy diffusion, and nonuniform flow. Molecular diffusion is due to thermally induced Brownian motion and is not significant compared to the other two phenomena. The latter two phenomena are functions of the degree of turbulence in the basin. Mixing is caused by two layers of water traveling at different velocities. Hydraulically induced motion is also referred to as orthokinetic motion. The velocity gradient (dv/dy) is proportional to the amount of energy dissipated in the fluid. Camp and Stein (1943) developed the basic theory of power input for mixing that is most commonly applied today.

To relate dv/dy to the power input into a basin, a force balance and power balance are needed. Newton's law of viscosity will be useful for calculating energy dissipation. For one-dimensional (1-D) flow it is

$$\tau_{yx} = -\mu \frac{dv_x}{dy} \tag{13.2}$$

where

τ_{yx} is the shear force per unit area in the x direction or the momentum transferred in the y direction resulting from motion in the x direction
μ is the dynamic viscosity
v_x is the velocity in the x direction
y is the vertical direction

A force (F) balance relates shear and pressure (p) forces (Fig. 13.3). Assuming 1-D laminar flow conditions for the elemental volume in Fig. 13.3,

$$\Sigma F_x = 0 = p\Delta y\,\Delta z - \left(p + \frac{\partial p}{\partial x}\Delta x\right)\Delta y\,\Delta z + \tau\Delta x\,\Delta z - \left(\tau + \frac{\partial \tau}{\partial y}\Delta y\right)\Delta x\,\Delta z \tag{13.3}$$

Expanding and simplifying Eq. (13.3),

$$\frac{\partial p}{\partial x} = -\frac{\partial \tau}{\partial y} \tag{13.4}$$

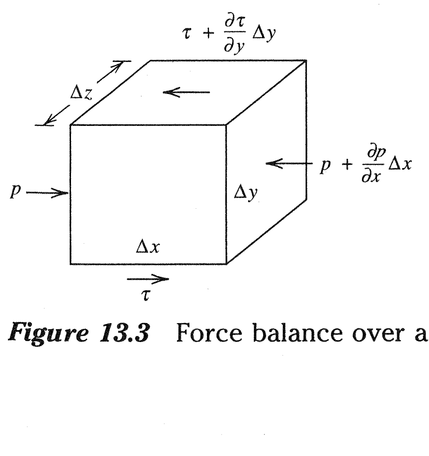

Figure 13.3 Force balance over an elemental volume of fluid.

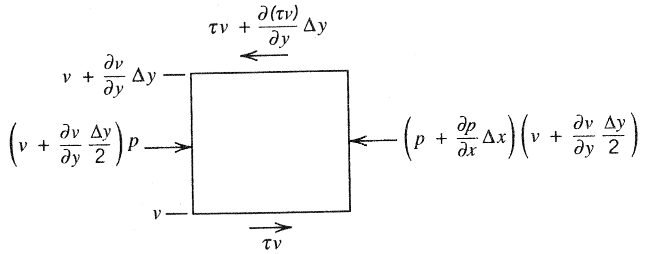

Figure 13.4 Power balance on an elemental volume.

The force balance is performed in a similar manner for the other two directions, although the gravity force is incorporated into the balance for the y direction.

A schematic for the power balance for an element (1-D flow) is shown in Fig. 13.4. Power is expressed by $P = \vec{F} \cdot \vec{v}$. Setting up the balance in the x direction for power into and out of the element,

$$P_{\text{in}} - P_{\text{out}} = \Delta P = \left(v + \frac{\partial v}{\partial y}\frac{\Delta y}{2}\right)p\Delta y\,\Delta z - \left(p + \frac{\partial p}{\partial x}\Delta x\right)\left(v + \frac{\partial v}{\partial y}\frac{\Delta y}{2}\right)\Delta y\,\Delta z \qquad (13.5a)$$
$$+ \tau v\,\Delta x\,\Delta z - \left(\tau v + \frac{\partial(\tau v)}{\partial y}\Delta y\right)\Delta x\,\Delta z$$

Expanding and simplifying Eq. (13.5a),

$$-v\frac{\partial p}{\partial x}\Delta x\,\Delta y\,\Delta z - v\frac{\partial \tau}{\partial y}\Delta x\,\Delta y\,\Delta z - \tau\frac{\partial v}{\partial y}\Delta x\,\Delta y\,\Delta z = \Delta P \qquad (13.5b)$$

Substituting the result of the force balance (Eq. 13.4) into the above equation and noting that $\Delta x \Delta y\,\Delta z = \Delta V$,

$$-\tau\frac{\partial v}{\partial y} = \frac{\Delta P}{\Delta V} \qquad (13.5c)$$

Applying Newton's law of viscosity (Eq. 13.2),

$$\mu\left(\frac{\partial v}{\partial y}\right)^2 = \frac{\Delta P}{\Delta V}$$

Assuming all elemental volumes are the same in this well-mixed basin,

$$\frac{\Delta P}{\Delta V} = \frac{P}{V}$$

and defining G as the velocity gradient, dv/dy,

$$\mu G^2 = \frac{P}{V} \qquad \text{and} \qquad G = \left(\frac{P}{\mu V}\right)^{1/2} \qquad (13.6)$$

P is the net power dissipated in the element. In fact, power will be dissipated in all three directions and G is the root-mean-square (rms) velocity gradient with dimensions of T^{-1}. Turbulent flow conditions normally exist in mixers and flocculators but Eq. (13.6) has been found to provide suitable results to relate power to mixing characteristics in basins regardless of the flow regime. The dimensionless number, Gt_d, has been correlated to performance of mixers and flocculators. For mixers, power dissipation should be high and time of reaction relatively short.

Calculation of the rate of energy dissipation depends upon the device used for mixing. Devices used for mixing range from power driven impellers to baffled basins. Power dissipation in hydraulic devices is due to the viscosity of the liquid. The equation for power dissipation in a hydraulic device is

$$P = \rho g Q h_{\mathrm{L}} \tag{13.7}$$

where

h_{L} is the headloss in the device
ρ is the density of the liquid.
g is the acceleration of gravity
Q is the volumetric flow rate

Once P is calculated it is inserted into Eq. (13.6) to find the velocity gradient. Expressions for other power dissipating devices are developed as they are discussed in the following sections.

13.3 MIXERS

Because coagulation reactions are rapid, a short detention time is all that is necessary, but a high degree of turbulence is required. The AWWA (1969) recommends design values in Table 13.3 for mixers in water treatment.

G values up to 5 000 s^{-1} have been used. Mixing units should be designed for the maximum day flow. Letterman et al. (1973) found the following empirical correlation that relates the key parameters of G, t_{d}, and concentration of coagulant for an impeller rapid mixing device using alum as a coagulant.

$$G t_{\mathrm{dopt}} C^{1.46} = 5.9 \times 10^{6}$$

where

t_{dopt} is the optimum detention time
C is the concentration of alum in mg/L

Conditioning chemicals are added to sludges to aid dewatering. High-shear conditions in the mixer can destroy the structure of the sludge. Kawamura (1991b) recommends G values of 100–150 s^{-1} for mixers that apply conditioning agents to sludge.

There are two means of coagulation: sweep coagulation and charge neutralization. During sweep coagulation, voluminous amounts of iron or aluminum hydroxide precipitates are formed to interact with the colloids in the raw water. In typical water treatment practice, the water is supersaturated three to four orders of magnitude beyond the solubility of the metal (iron or aluminum) so that the metal hydroxide precipitates quickly in 1–7 s (AWWA Committee, 1989). Transport interaction between colloids and coagulants during initial coagulant addition and rapid mixing are less important than the subsequent flocculation step.

TABLE 13.3 G–t_{d} Values for Mixers[a]

t_{d}, s	20	30	40	>40
G, s^{-1}	1 000	900	790	700

[a] After AWWA (1969).

For charge neutralization to occur effectively, the coagulants must be dispersed rapidly (<0.1 s is desirable) and high-intensity mixers are required (AWWA Committee, 1989). When the metal coagulant is added to the water, within microseconds up to a second, charged metal hydrolysis products are formed. These charged species must be transported to the colloids before the ultimate hydroxide precipitation product is formed.

13.3.1 Mechanical Mixers

Impeller driven mixers are the most efficient devices to rapidly disperse coagulants. Mixing in these devices is a function of the geometry of the basin and impeller, fluid characteristics, and power expenditure (Uhl and Gray, 1966). Gravity effects are generally not important. Correlations for power input and the Reynold's number (Re) have been developed for many types of mixing devices.

The following relations exist in an impeller mixer:

$$v \propto ND \tag{13.8a}$$

$$A \propto D^2 \tag{13.8b}$$

$$P \propto F_D v = F_D ND \tag{13.8c}$$

where

v is velocity of the impeller
N is the rate of revolution
D is the impeller diameter
F_D is the drag force
P is the power expenditure

Using relations in Eqs. (13.8a)–(13.8c) a power number analogous to a drag coefficient or friction factor is formulated. A drag coefficient is the ratio of drag force to kinetic energy of the impeller and a characteristic area.

$$C_D = \frac{2F_D}{\rho A v^2} = \frac{2F_D v}{\rho A v^3} \tag{13.9a}$$

$$\phi = \frac{P}{\rho N^3 D^5} \tag{13.9b}$$

where

C_D is a drag coefficient
ϕ is the power number

The Reynold's number for the impeller is

$$\mathrm{Re} = \frac{\rho N D^2}{\mu} \tag{13.10}$$

From experiment it is found that

$$\phi = K\mathrm{Re}^p \tag{13.11}$$

where

K is a characteristic constant of an impeller and tank geometry
$p = -1$ (laminar)
$\quad = 0$ (turbulent)

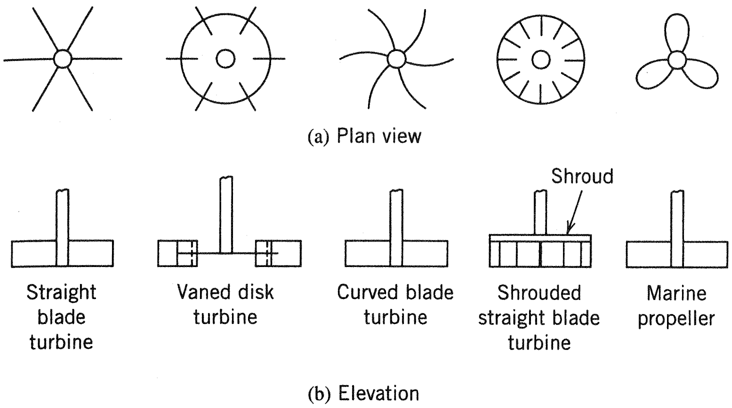

Figure 13.5 Types of impellers.

The laminar or viscous range exists when Re $\lesssim 10$. For fully developed turbulent flow the power number is constant.

Types of impellers are shown in Fig. 13.5. The following definitions apply to impellers.

Propeller	an impeller that is curved around its axis in a screwlike manner.
Pitch	the advance per revolution considering the propeller as a screw. A square pitch means the pitch is equal to the diameter.
Turbine (Fig. 13.6)	the blade may be flat or curved.
Shroud	a full or partial plate added to the top or bottom planes of a radial flow turbine.

A typical plot of power number variation with the Reynold's number is given in Fig. 13.7 (note its similarity to a Moody diagram). Similar plots should be developed for each configuration.

Table 13.4 lists experimentally determined values of K for various types of impellers in a circular tank where vortex conditions have been eliminated by having four baffles at the tank wall, each with a length of 10% of the tank diameter. Separate correlations should be developed for each tank–impeller configuration. Equation (13.11), with coefficients given in Table 13.4, applies only to the straight portions of the curve in Fig. 13.7.

Under turbulent flow conditions, power requirements in a baffled vertical circular tank are the same as power requirements for a baffled vertical square tank when the diameter of the circular tank is equal to the width of a square tank (Reynolds, 1982).

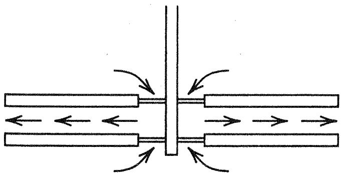

Figure 13.6 Radial flow turbine.

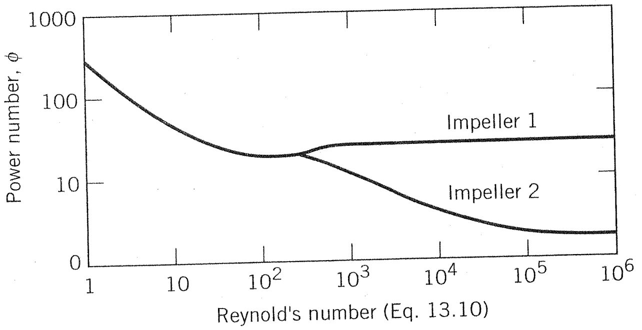

Figure 13.7 Typical plot of power number as a function of the Reynold's number. Reprinted with permission from J. H. Rushton (1952), "Mixing of Liquids in Chemical Processing," *Industrial and Engineering Chemistry,* 44, 12, pp. 2931–2936, copyright 1952, American Chemical Society.

In an unbaffled square tank the power imparted is about 75% of the power imparted in a baffled square or a baffled circular tank (Reynolds, 1982).

TABLE 13.4 Power Coefficients for Various Impellers[a,b]

Impeller	Viscous range	Turbulent range
Propeller, square pitch, 3 blades	41.0	0.32
Propeller, pitch of 2, 3 blades	43.5	1.00
Turbine, 4 flat blades, vaned disk	71.0	6.30
Turbine, 6 flat blades, vaned disk	71.0	6.30
Turbine, 6 curved blades	70.0	4.80
Turbine, 6 arrowhead blades	71.0	4.00
Fan turbine, 6 blades at 45°	70.0	1.65
Flat paddle, 2 blades	36.5	1.70
Shrouded turbine, 2 curved blades	97.5	1.08
Shrouded turbine, 6 curved blades	97.5	1.08
Shrouded turbine with stator, no baffles	172.5	1.12
Flat paddles, 2 blades, $D/w^c = 6$	36.5	1.60
Flat paddles, 2 blades, $D/w^c = 8$	33.0	1.15
Flat paddles, 4 blades, $D/w^c = 6$	49.0	2.75
Flat paddles, 6 blades, $D/w^c = 6$	71.0	3.82

[a] Reprinted with permission from J. H. Rushton (1952), "Mixing of Liquids in Chemical Processing," *Industrial and Engineering Chemistry,* 44, 12, pp. 2931–2936, copyright 1952, American Institute of Chemical Engineers; and J. H. Rushton and J. Y. Oldshue (1953), "Mixing—Present Theory and Practice," *Chemical Engineering Progress,* 49, 4, pp. 161–168, used with permission of the American Institute of Chemical Engineers.

[b] For baffled cylindrical tanks with four baffles at the tank wall, baffle width is 10% of the tank diameter. The impeller width is one third of tank diameter, *D*.

[c] *w* is the impeller width.

13.4 FLOCCULATORS

There are a wide variety of devices that can be used to accomplish the more gentle mixing required for flocculation. Basins with mechanically driven paddles are common. Also, pneumatic flocculators designed on the principles given in Section 13.3.2 can be used. Devices in the hydraulic category are pipes, baffled channels, pebble bed flocculators, and spiral flow tanks. Headloss calculations are made from basic fluid mechanics principles.

The work of Smoluchowski (1916) relates particle contact to the velocity gradient or G. Many studies have shown that flocculation efficiency is related to the G value. As noted, Eq. (13.6) was developed for laminar flow and assumed to apply to turbulent flow. Recently Cleasby (1984) has made a thorough theoretical analysis of flocculation and power dissipation in turbulent flow. He has given convincing arguments that G is related to $(P/V)^{2/3}$ under some conditions. Note that viscosity is absent in this expression; thus, temperature does not influence the phenomenon. The development is beyond the scope of this text but it does indicate that flocculation efficiency should be compared against $(P/\mu V)^{1/2}$ and $(P/V)^{2/3}$ to determine the better correlation for design and operation. In most cases the former relation is applicable.

Flocculators are commonly designed to have Gt_d values in the range of 10^4 to 10^5. G values may range from 10 to 60 s^{-1} and detention times are typically in the range of 15–45 min. Mixing in an individual flocculator basin causes the hydraulic flow regime to approach complete mixed conditions. Therefore, it is desirable to have two or more basins in series to ensure that all particles are exposed to the mixing for a significant amount of the total detention time and to promote plug flow through the system as a whole. Furthermore, providing basins in series allows the G value to be decreased from one compartment to the next as the average floc size increases. This is known as tapered flocculation, which produces better results. The total detention time for all compartments should be in the range suggested above. Units are also designed in parallel or with bypasses to allow for a unit being taken out of service.

Paddle Flocculators

Paddle flocculators have compartments that each have one or more sets of paddles mounted in them. The paddles may be oriented in any direction; Figs. 13.10 and 13.11 show two orientations. The useful power input imparted by a paddle to the fluid

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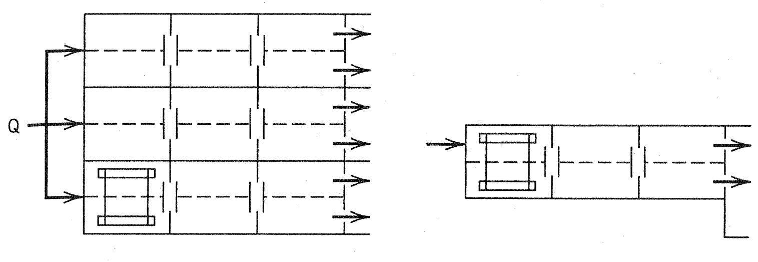


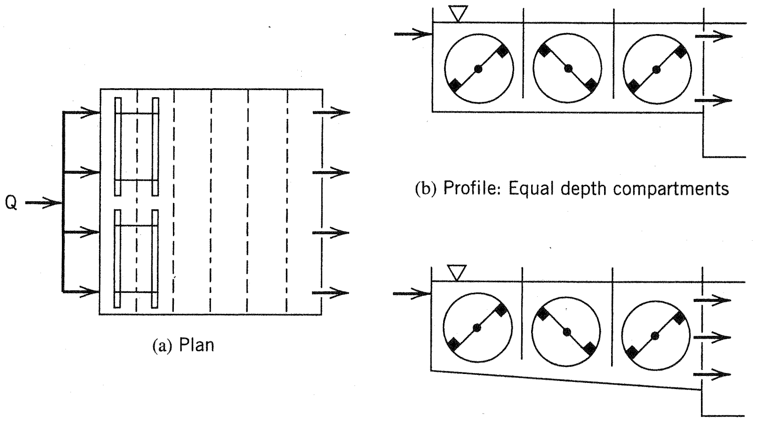
(a) Plan (b) Profile

Figure 13.10 Horizontal flow paddle flocculator with blades parallel to flow. Adapted from AWWA (1969). Reprinted from *Water Treatment Plant Design*, by permission. Copyright © 1969, American Water Works Association.

depends on the drag force and the relative velocity of the fluid with respect to the paddle. A schematic of a paddle blade is shown in Fig. 13.12. The following symbol definitions apply to the sketch.

v_f = fluid velocity
v_p = paddle velocity
r_i = distance from shaft to inner edge of the paddle
r_o = distance from shaft to outer edge of the paddle
b = length of the paddle
N = rate of revolution of the shaft (rpm)

The velocity of the fluid will be less than the velocity of the paddle by a factor, k, because of slip. If baffles (called stators) are placed along the walls in a direction



(a) Plan

(b) Profile: Equal depth compartments

(c) Profile: increasing depth compartments

Figure 13.11 Horizontal flow paddle flocculators with blades perpendicular to flow. Adapted from AWWA (1969). Reprinted from *Water Treatment Plant Design*, by permission. Copyright © 1969, American Water Works Association.

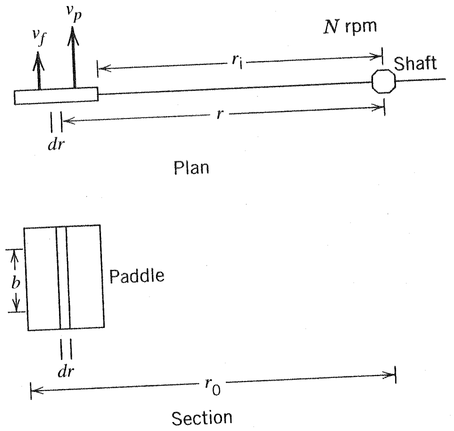


Figure 13.12 Paddle blade in a flocculator.

perpendicular to the fluid movement, the value of k decreases because these baffles obstruct the movement of fluid. The frictional dissipation of energy depends on the relative velocity, v.

$$v = v_p - v_f = v_p - kv_p = v_p(1 - k) \tag{13.21}$$

The velocity of the paddle at a distance r from the shaft is

$$v_p = \frac{2\pi N}{60} r \tag{13.22}$$

The equation for drag force of the paddle on the fluid is the usual equation,

$$F_D = \tfrac{1}{2}\rho C_D A v^2$$

where

A is the area of the paddle
F_D is the drag force
C_D is a drag coefficient

The power input imparted to the fluid by an elemental area of the paddle is

$$dP = dF_D \cdot v = \tfrac{1}{2}\rho C_D v^3\, dA \tag{13.23}$$

Noting that $dA = b\ dr$ and substituting Eqs. (13.21) and (13.22) into Eq. (13.23) and integrating,

$$\begin{aligned} P &= \frac{1}{2}\rho C_D b \left[\frac{2\pi N}{60}(1 - k)\right]^3 \int_{r_i}^{r_o} r^3\, dr \\ &= (1.44 \times 10^{-4}) C_D \rho b [N(1 - k)]^3 (r_o^4 - r_i^4) \end{aligned} \tag{13.24}$$

(SI: ρ, kg/m^3; b, m; r, m; P, watts)
(U.S.: ρ, slug/ft^3; b, ft; r, ft; P, ft-lb/s)

There is usually more than one set of paddles on each arm of the shaft. Equation (13.24) should be applied individually to each paddle and the results summed to obtain

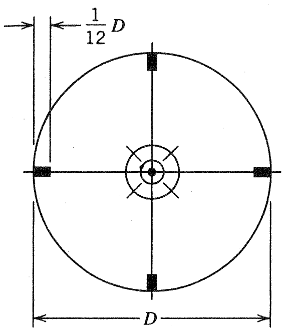


Figure 13.13 Paddle with stators.

the total power dissipation. Recommended design parameters for a paddle flocculator are as follows:

Peripheral speed of the paddles, 0.09–0.9 m/s (0.3–3 ft/s)

$k = 0.25$ without stators, 0–0.15 with stators

$C_D \approx 1.8$ for flat blades

Area of the blades is 15–20% of the tank cross-sectional area (if the paddles are oriented parallel to the flow, use 15–20% of the tank side area).

There are no specific guidelines for depth–area ratios in a paddle flocculator but the maximum depth should not exceed 5 m (16.4 ft) or unstable flows will result (Montgomery, 1985). Ground levels and plant layout dictate feasible depths. A freeboard of 0.5 m (1.6 ft) should be provided. If flocculators are followed by rectangular, horizontal flow sedimentation basins, the widths in both basins should be the same.

A section with a paddle arm and stators is shown in Fig. 13.13. The spacing, size, and number of paddles on a paddle arm can be varied to provide different G values. Variable speed motors should be provided to change the power input as required with changes in temperature, flow rate, and water quality. There must be space for shaft supports between adjacent paddle sets.

The compartments in a paddle flocculator are often separated with a baffle wall (Fig. 13.14) to equalize flow distribution. When sedimentation tanks directly follow

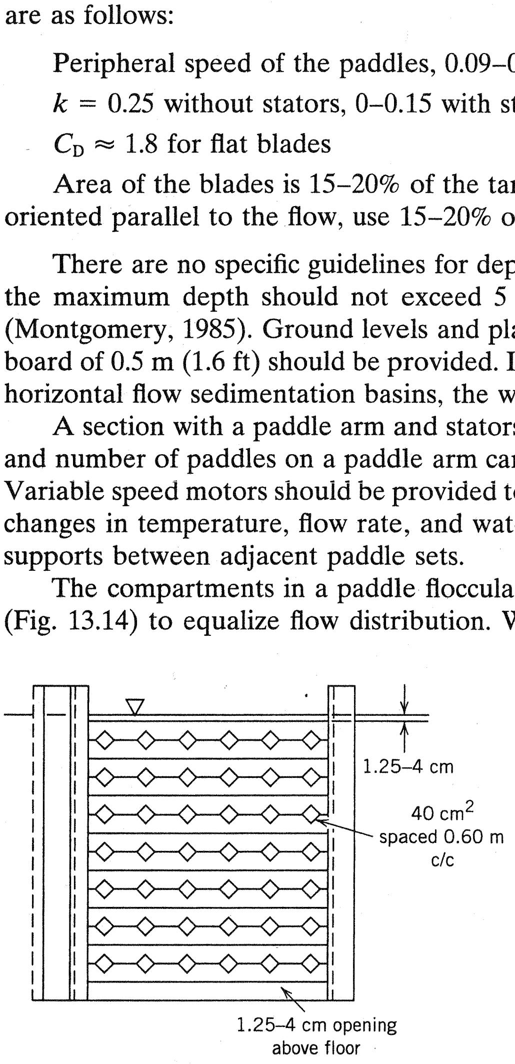


Figure 13.14 Typical baffle wall. Adapted from J. M. Montgomery, Consulting Engineers, Inc. (1985), *Water Treatment Principles and Design,* copyright © 1985 by John Wiley & Sons, Inc. Reprinted by permission of John Wiley & Sons, Inc.

flocculation basins, baffle walls (also known as diffuser walls) are the preferred inlet devices. Design guidelines for baffle walls vary among various sources (ASCE and AWWA, 1990; Kawamura, 1973, 1991b). The area of the baffle orifices is approximately 3–6% of the wall area or provides a velocity of 0.3 m/s (1 ft/s) under maximum flow conditions (ASCE and AWWA, 1990; Kawamura, 1973). The size of an orifice should be between 40 and 175 cm^2 (6–27 in.^2). The baffle wall is raised 1.25–4 cm (0.5–1.5 in.) above the floor to allow easy cleaning of sludge deposits. A water clearance of 1.25–4 cm (0.5–1.5 in.) over the baffle wall is provided to pass scum through the flocculator. Orifice size and spacing is somewhat variable to meet the flow-through velocity constraint. Uniform flow through the baffle wall is assumed and the area above and below the baffle wall is ignored.

Turbines or propellers may be used instead of paddles. It will be difficult to install a paddle system in a small installation. Propeller area will not be 15–20% of the cross-sectional area. Equations (13.9b), (13.10), and (13.11) would be used to calculate power and rotational speed requirements. Monk and Trussell (1991) provide equations and the design procedure for vertical shaft flocculators and Amirtharajah (1978) provides a design example for an axial flow propeller flocculator.

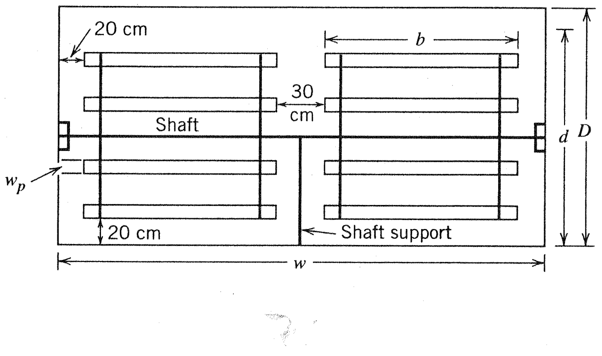
■ Example 13.2 Paddle Flocculator Design

Design a three-compartment flocculator with the configuration of Fig. 13.11b to treat a design flow of 15 000 m^3/d (3.96 Mgal/d). The design G values are 45, 20, and 10 s^{-1} in each successive compartment and the total detention time in the flocculator will be 30 min. The maximum length of an individual paddle should not exceed 3.5 m (11.5 ft) and the width of a paddle should be between 10 and 20 cm (0.33–0.66 ft). The minimum clear space between the outer paddle and the floor and water surface should be 20 cm (8 in.). Shaft supports require a 30-cm (1-ft) spacing. The distance of a paddle from a wall should be at least 20 cm (8 in.). The lowest temperature expected is 10°C, which is the design temperature. Use 1 : 4 variable speed motors. The maximum depth (D) of the flocculator is 4.3 m (14.1 ft). Assume C_D and k are 1.8 and 0.25, respectively.

The total volume (V) of the flocculator is

$$V = Qt_\text{d} = \left(15\,000\,\frac{\text{m}^3}{\text{d}}\right)(30\text{ min})\left(\frac{1\text{ h}}{60\text{ min}}\right)\left(\frac{1\text{ d}}{24\text{ h}}\right) = 313\text{ m}^3$$

$$\text{In U.S. units: } V = \left(3.96 \times 10^6\,\frac{\text{gal}}{\text{d}}\right)(30\text{ min})\left(\frac{1\text{ h}}{60\text{ min}}\right)\left(\frac{1\text{ d}}{24\text{ h}}\right)\left(\frac{1\text{ ft}^3}{7.48\text{ gal}}\right) = 11\,029\text{ ft}^3$$



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For a single compartment use a volume of 104 m^3 ($\approx$ 313 m^3/3) (similarly, the volume of a chamber in U.S. units is 3 676 ft^3). The effective depth (d) is 3.80 m (12.5 ft) with a freeboard of 0.50 m (1.64 ft or 20 in.).

With shafts located in the center of the compartment, the maximum length of a paddle arm (l_a) is determined from the surface and floor clearances and the depth.

$$l_a = \tfrac{1}{2}(3.80\ \text{m} - 2 \times 0.20\ \text{m})$$
$$= 1.70\ \text{m}$$
$$\text{In U.S. units: } l_a = \tfrac{1}{2}(12.5\ \text{ft} - 2 \times 1.64\ \text{ft}) = 4.60\ \text{ft}$$

(A single paddle arm would exceed the maximum length specification.) The minimum length of a compartment (l_c), considering wall spacings, is

$$l_c = 2l_a + 2 \times 0.20\ \text{m} = 2(1.70\ \text{m}) + 0.40\ \text{m} = 3.80\ \text{m}$$
$$\text{In U.S. units: } l_c = 2l_a + 2 \times 0.66\ \text{ft} = 2(4.60\ \text{ft}) + 1.32\ \text{ft} = 10.5\ \text{ft}$$

The cross-sectional area (A) and width (w) of a compartment (and the basin) are

$$A = (104\ \text{m}^3)/(3.80\ \text{m}) = 27.4\ \text{m}^2 \qquad w = (27.4\ \text{m}^2)/(3.80\ \text{m}) = 7.20\ \text{m}$$
$$\text{In U.S. units: } A = (3\ 676\ \text{ft}^3)/(12.5\ \text{ft}) = 294\ \text{ft}^2 \qquad w = (294\ \text{ft}^2)/(12.5\ \text{ft}) = 23.5\ \text{ft}$$

Two adjacent sets of paddles can be installed in this width. A sketch of the front view of the flocculator is shown earlier. The available width (w_a) is determined by subtracting the wall clearance and shaft support widths from the total width.

$$w_a = 7.20\ \text{m} - 0.30\ \text{m} - (2 \times 0.20\ \text{m}) = 6.50\ \text{m}$$
$$\text{In U.S. units: } w_a = 23.5\ \text{ft} - 1.0\ \text{ft} - (2 \times 0.66\ \text{ft}) = 21.2\ \text{ft}$$

The length of a paddle (b) will be 3.25 m (10.6 ft). Choose the area of the paddles (A_p) to be 17% of the cross-sectional area

$$A_p = 0.17\ (27.4\ \text{m}^2) = 4.66\ \text{m}^2 \qquad \text{in U.S. units: } A_p = (0.17)(294\ \text{ft}^2) = 50.0\ \text{ft}^2$$

If each paddle set has four paddles, the width of a paddle (w_p) is

$$w_p = (4.66\ \text{m}^2)/8/(3.25\ \text{m}) = 0.18\ \text{m} = 18\ \text{cm}$$
$$\text{In U.S. units: } w_p = (50.0\ \text{ft}^2)/8/(10.6\ \text{ft}) = 0.59\ \text{ft} = 7.1\ \text{in.}$$

This is a suitable paddle width. Therefore each paddle set will include four paddles. The outer paddle will be located at the end of the paddle arm. The inner paddle will be located midway between the shaft and the outer paddle.

The power requirement for the first chamber is

$$P = \mu V G^2 = (1.307 \times 10^{-3}\ \text{kg/s-m})(104\ \text{m}^3)(45\ \text{s}^{-1})^2 = 275.3\ \text{W} \tag{i}$$
$$\text{In U.S. units: } P = \left(2.735 \times 10^{-5}\frac{\text{lb-s}}{\text{ft}^2}\right)(3\ 676\ \text{ft}^3)(45\ \text{s}^{-1})^2\left(\frac{1\ \text{hp}}{550\,\frac{\text{ft-lb}}{\text{s}}}\right) = 0.370\ \text{hp}$$

The power expenditure for a paddle (P_p) is

$$P_p = (1.44 \times 10^{-4})C_D\rho b[N(1-k)]^3(r_o^4 - r_i^4)$$
$$P_p = (1.44 \times 10^{-4})(1.8)(999.7)(3.25)(0.75)^3N^3(r_o^4 - r_i^4) = 0.355N^3(r_o^4 - r_i^4)$$
$$\text{In U.S. units: } P_p = (1.44 \times 10^{-4})(1.8)(1.94)(10.6)(0.75)^3N^3(r_o^4 - r_i^4) = 0.002\ 25N^3(r_o^4 - r_i^4)$$

For an outer paddle with inner and outer radii of 1.52 and 1.70 m (5.00 and 5.59 ft), respectively, the power expenditure (P_o) is

$$P_o = 0.355N^3[(1.70)^4 - (1.52)^4] = 1.071N^3 \text{ W}$$

$$\text{In U.S. units: } P_o = 0.002\,25N^3[(5.59)^4 - (5.00)^4] = 0.791N^3 \text{ ft-lb/s}$$

For an inner paddle with inner and outer radii of 0.76 and 0.94 m (2.49 and 3.08 ft), respectively, the power expenditure (P_i) is

$$P_i = 0.355N^3[(0.94)^4 - (0.76)^4] = 0.159N^3 \text{ W}$$

$$\text{In U.S. units: } P_i = 0.002\,25N^3[(3.08)^4 - (2.49)^4] = 0.116N^3 \text{ ft-lb/s}$$

The total power expenditure in the compartment as a function of N is

$$\begin{aligned} P &= 4(P_o + P_i) = 4(1.071 + 0.159)N^3 = 4.92N^3 \text{ W} \\ \text{In U.S. units: } P &= 4(0.791 + 0.116)N^3 = 3.63N^3 \text{ ft-lb/s} \end{aligned} \tag{ii}$$

By definition in Section 13.4, the units on N are rpm. N is found by equating Eqs. (i) and (ii).

$$N = \left(\frac{275.3}{4.92}\right)^{1/3} = 3.82 \text{ rpm}$$

$$N = \left[\frac{(0.370 \text{ hp})\left(550 \dfrac{\text{ft-lb/s}}{\text{hp}}\right)}{3.63}\right]^{1/3} = 3.83 \text{ rpm}$$

The peripheral velocity of the outer paddle (Eq. 13.22) is

$$v_p = \frac{2\pi N}{60} r = \frac{2\pi(3.82 \text{ rev/min})}{60 \text{ s/min}}(1.70 \text{ m}) = 0.68 \text{ m/s}$$

$$\text{In U.S. units: } v_p = \frac{2\pi(3.82 \text{ rev/min})}{60 \text{ s/min}}(5.59 \text{ ft}) = 2.24 \text{ ft/s}$$

which is within the acceptable range of 0.09–0.9 m/s (0.3–3 ft/s).

Choosing the design N value to be in the middle of the range for a 1:4 variable speed motor, the following relations exist between the minimum, maximum, and middle rotational speeds (N_{min}, N_{max}, and N_{mid}, respectively).

$$\frac{N_{\text{min}} + N_{\text{max}}}{2} = N_{\text{mid}} \quad N_{\text{max}} = 4N_{\text{min}} \quad N_{\text{min}} = 0.4N_{\text{mid}}$$

Therefore, $N_{\text{min}} = 1.53$ rpm and $N_{\text{max}} = 6.12$ rpm.

The required G values in the second and third compartments are obtained by reducing the rotational speed of the paddles in these compartments. For the second compartment, the G value is 20 s^{-1}. Using Eq. (i), the power dissipation in the compartment is

$$\begin{aligned} P = \mu V G^2 &= (1.307 \times 10^{-3} \text{ kg/s-m})(104 \text{ m}^3)(20 \text{ s}^{-1})^2 \\ &= 54.4 \text{ W} \end{aligned}$$

Using Eq. (ii), N is found to be

$$N = \left(\frac{54.5}{4.92}\right)^{1/3} = 2.23 \text{ rpm}$$

(5.00 and 5.59 ft),

W

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The peripheral velocity of the outer paddle is

$$v_p = \frac{2.23}{3.82}(0.68) = 0.40\ \text{m/s}$$

The speed range of the motor is from 0.89 to 3.57 rpm.
Similar calculations for the third compartment yield

$$P = 13.6\ \text{W} \qquad N = 1.40\ \text{rpm} \qquad v_p = 0.25\ \text{m/s}$$

The speed range of the motor is from 0.56 to 2.24 rpm.

■ Example 13.3 Baffle Wall Design

Design baffle walls to be placed between compartments and at the exit end of the flocculator in the previous example. Calculate the headloss through the baffle wall. Use a design similar to Fig. 13.14 with sharp-edged, diamond-shaped orifices.

The width of the basin is 7.20 m (23.5 ft) and its effective depth is 3.80 m (12.5 ft). The design flow is

$$Q = 15\,000\ \text{m}^3/\text{d} = \left(15\,000\frac{\text{m}^3}{\text{d}}\right)\left(\frac{1\ \text{d}}{86\,400\ \text{s}}\right) = 0.174\ \text{m}^3/\text{s}\ (6.13\ \text{ft}^3/\text{s})$$

The velocity through the baffle wall should not exceed 0.3 m/s (1 ft/s). The total area of the orifices is

$$v = Q/\Sigma a \qquad \Sigma a = Q/v = (0.174\ \text{m}^3/\text{s})/(0.3\ \text{m/s}) = 0.580\ \text{m}^2\ (6.24\ \text{ft}^2)$$

If an orifice has sides of 7 cm and an opening of 49 cm^2 (0.004 9 m^2), the number of orifices is

$$N = (0.580\ \text{m}^2)/(0.004\,9\ \text{m}^2) = 118$$

Define the number of orifices per unit height and unit width as n_h and n_w, respectively. A clearance of 1.5 cm will be provided above and below the baffle wall. The height of the baffle wall will be 3.77 m (12.4 ft). Then for uniform spacing of the orifices,

$$n_h n_w = N \qquad \frac{n_h}{3.77} = \frac{n_w}{7.20} \qquad \frac{7.20}{3.77}n_h = n_w \qquad 1.91n_h = n_w$$

$$1.91n_h^2 = N \qquad n_h = \sqrt{\frac{118}{1.91}} = 7.9 \qquad n_w = 1.91(7.9) = 15.1$$

Choose n_h and n_w to be 8 and 15, respectively. The total number of orifices is 8 × 15 = 120. Space the orifices (7.20 m)/15 = 0.48 m (1.57 ft) c/c horizontally and (3.77 m)/8 = 0.47 m (1.54 ft) c/c vertically.

The flow through an orifice is

$$q = Q/N = (0.174\ \text{m}^3/\text{s})/120 = 0.001\,45\ \text{m}^3/\text{s}\ (0.051\,2\ \text{ft}^3/\text{s})$$

The velocity through an orifice will be less than 0.3 m/s (1 ft/s) because the number of orifices has been slightly increased and there will be some flow over and under the baffle wall.