

Islamic University of Gaza -Environmental Engineering Department

Water Treatment

EENV 4331

Lecture 3: Coagulation and Flocculation

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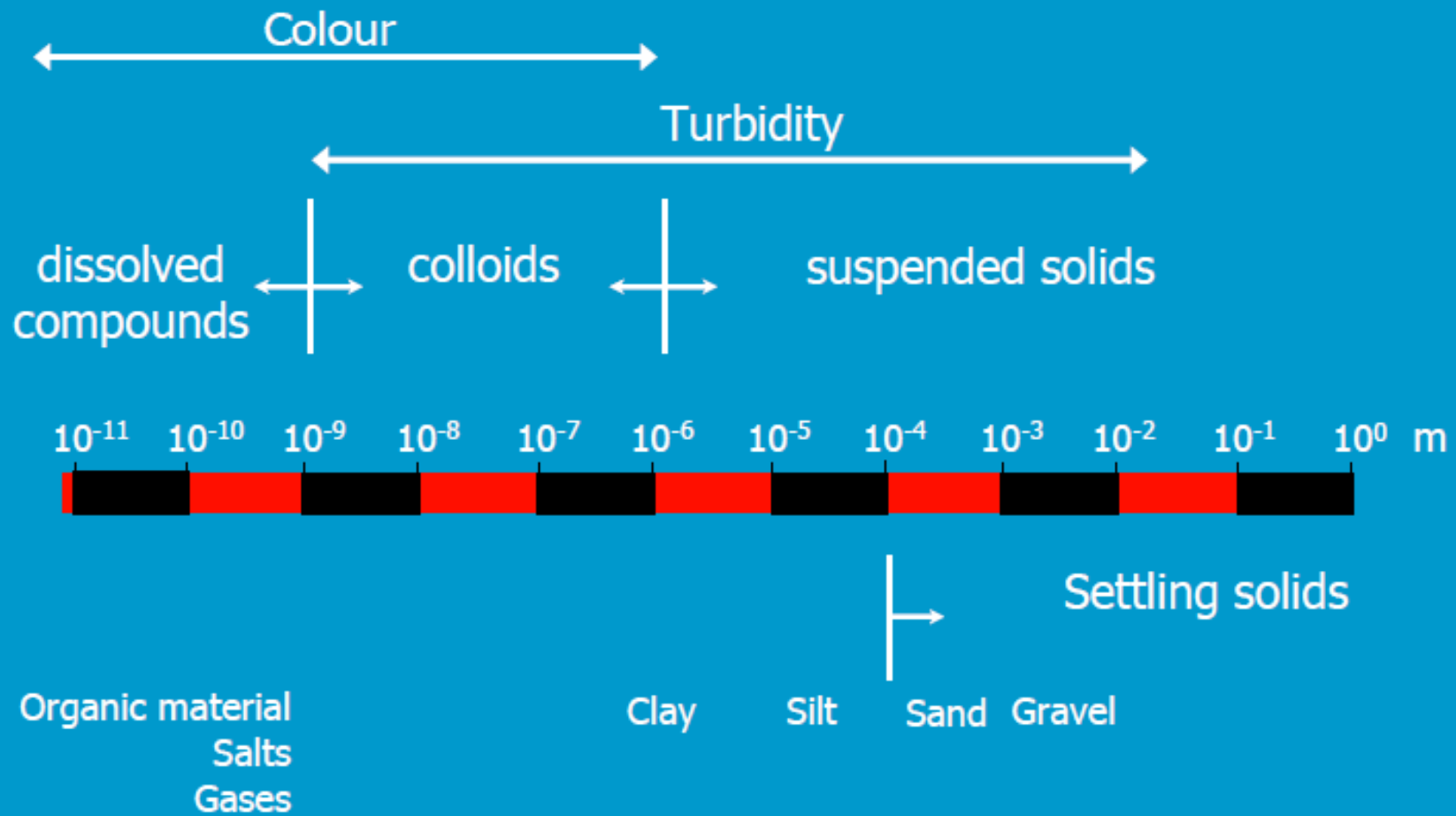
3.1 Definition of Coagulation and Flocculation

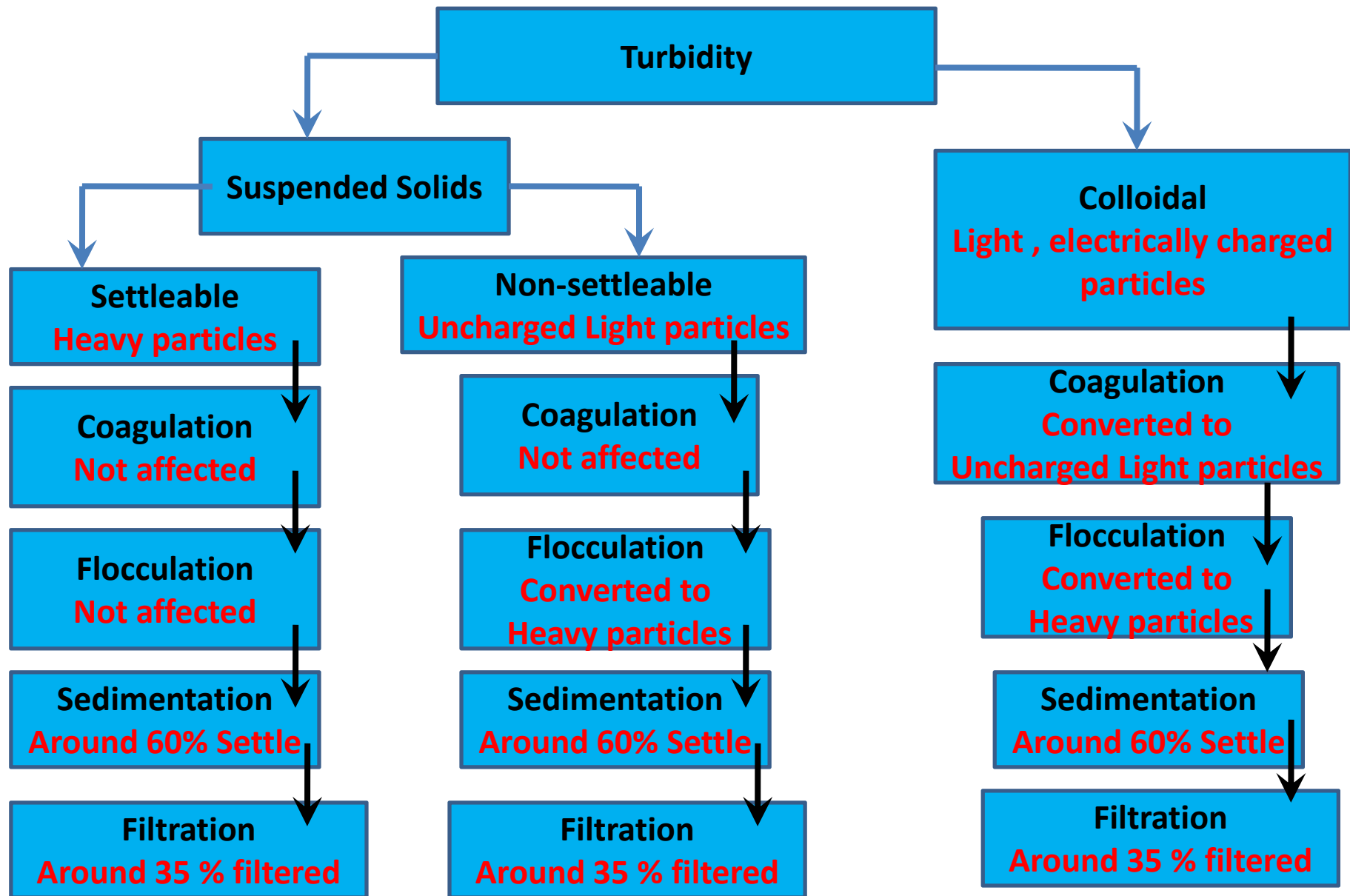
- ❑ Coagulation and flocculation are two consecutive process (i.e. occur one after the other) that are used to remove colloidal particles from water.
- ❑ Colloids are very small particles (turbidity and color causing particles) that can not be removed neither by sedimentation (due to their light weight) nor by filtration.
- ❑ Examples of colloids: soil particles, bacteria, viruses and color causing materials. These colloids are stable in solution and theoretically will stay there for ever unless an action is done to destabilize them. Coagulation and flocculation are the two processes used for this destabilization.

3.2 Colloidal Stability

- ❑ Colloids are very Small particles (0.01 to 1 μm)
- ❑ Most naturally occurring particles in water are negatively charged.
Since like charges repel, these small particles, or colloids, will remain suspended almost indefinitely.
- ❑ A fixed layer of **positive** ions (counterions) is attracted to the **negatively** charged colloids by electrostatic attraction. This layer is called **stern layer** or fixed layer. This layer is surrounded by a movable **diffuse layer** of counterions but with a lower concentration than that in the fixed layer. The two layers form what is called the **double layer theory**.

Classification





Turbidity removal flowchart from surface water

- ❑ The surface between the two layers is called the shear surface. When the colloid moves the fixed layer moves with it.
- ❑ The positive charge attached to the colloid in the **stern layer** is not enough to neutralize the negative charge of the colloid. So there is a net electrical potential around the colloid as shown in the **Figure 3.1**.
- ❑ The Electrical potential at the shear surface is called the **Zeta potential** which is a measure of the repulsive force of the colloid to other colloids having the same charge.

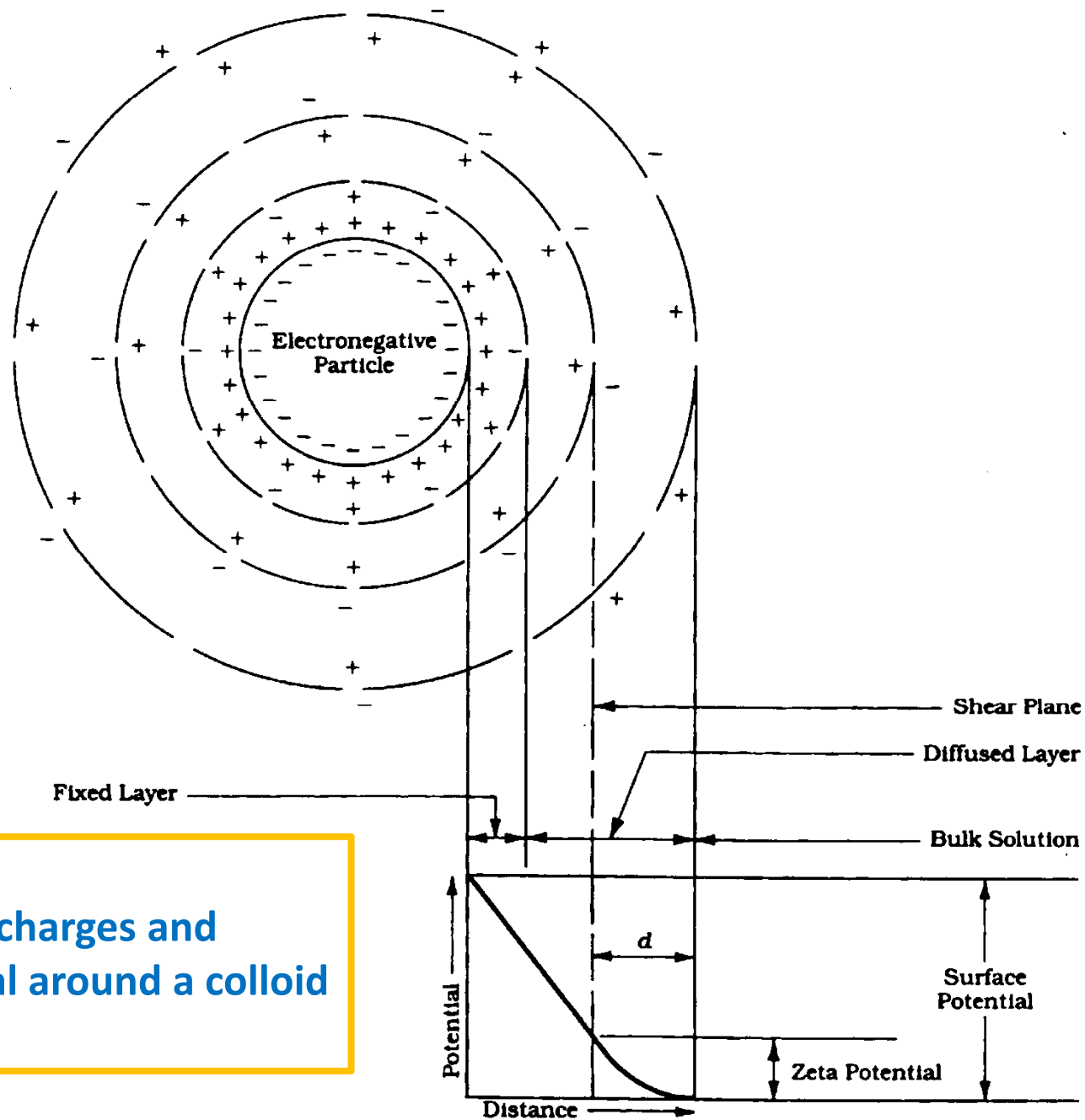


Figure 3.1:
Double layer charges and
Zeta potential around a colloid

□ There are two major forces acting on colloids:

1) Electrostatic repulsion

negative colloids **repel** other negatively charged colloids

$$F_{ES} \propto \frac{1}{d^2}, \text{ Electrostatic repulsion Force}$$

2) Intermolecular attraction, or van der Waals,.

$$F_{Van} \propto \frac{1}{d^6}, \text{ Van der Waal attraction Force}$$

For a stable colloid the net energy is repulsive.

Figures 3.2 and 3.3 Illustrates these two main forces.

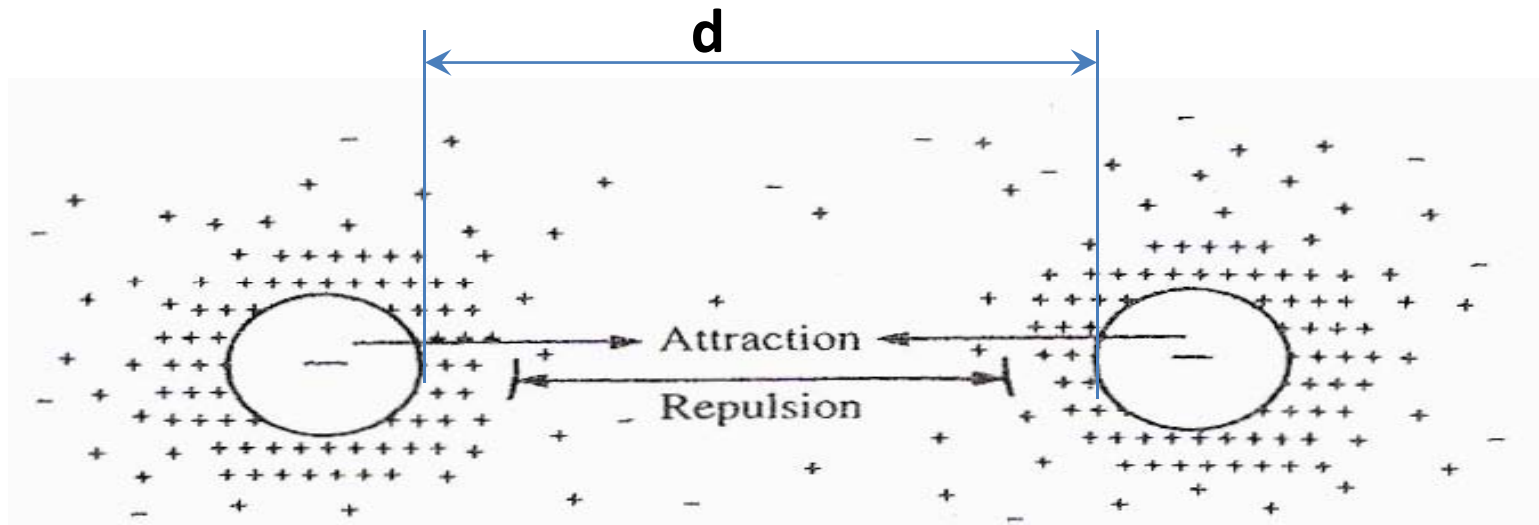


Figure 3.2:
Forces affecting colloids : Electrostatic repulsion and Van-der Waal attraction

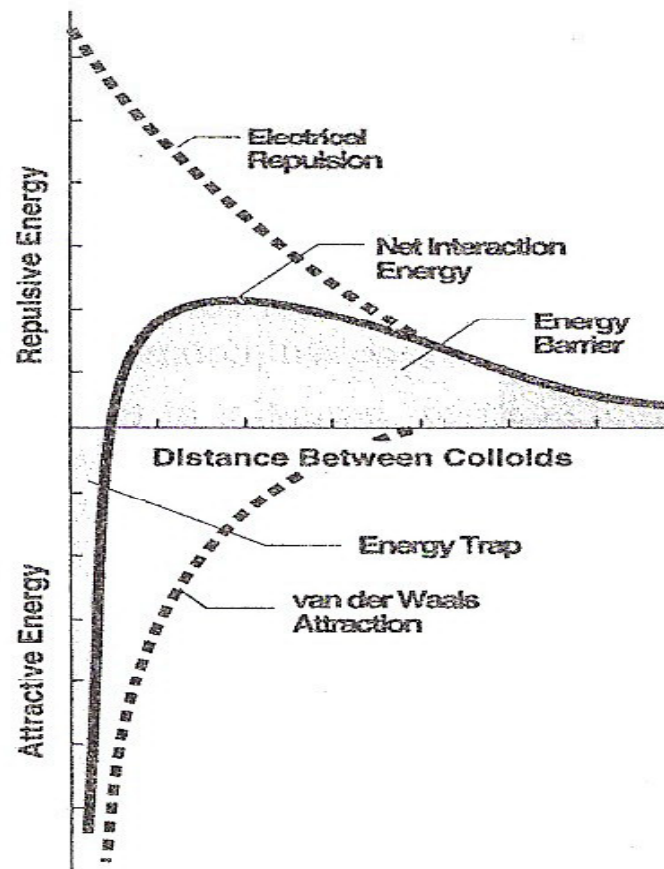


Figure 3.3:
Forces affecting colloids : Electrostatic repulsion and Van-der Waal attraction

3.3 Colloidal Destabilization and agglomeration

1. Colloidal Destabilization or Coagulation:

- ❑ It was illustrated that colloids are **stable** due to the net repulsive force between them consequently they will stay stable in suspension unless this net repulsive force is neutralized .
- ❑ The process of neutralization of the repulsive force is called **destabilization** .
- ❑ **Destabilization** is achieved by a process called **coagulation**.
- ❑ **Coagulation** is the process of destabilization of colloids by adding chemicals (**Coagulants**) with a **counter charge** to neutralize the charge carried by the colloids. This will reduce the repelling force and gives the opportunity for the attractive forces to prevail and allow the particles and make them ready to agglomerate and form bigger particles.

3.3 Colloidal Destabilization and agglomeration

2. Agglomeration or Flocculation (Forming Flocs):

- ❑ After destabilization (i.e. **Coagulation**), particles will be ready to attract and agglomerate and form **flocs**. But this agglomeration is slow and they **need help** to accelerate this agglomeration.
- ❑ This help is called **Flocculation** “which is the slow stirring or gentle agitation to aggregate the destabilized particles and form a rapid settling floc”.
- ❑ This gentle mixing increases the collisions between the particles and help them to agglomerate. Notice that rapid mixing will destroy the flocs, that's why we need gentle mixing.

3.4 Coagulation

1. Coagulants:

- ❑ Coagulants are chemicals that are added to water to destabilize colloids.

The most common coagulants are given in the table below:

Type of coagulant	formula	most common form	N
aluminum sulfate	$\text{Al}_2 (\text{SO}_4)_3 \cdot 14-18 \text{H}_2\text{O}$	lumps or powder	acidic
Sodium aluminate	NaAlO_2 or $\text{Na}_2\text{Al}_2\text{O}_4$	Powder	alkaline
Poly-aluminiumchloride	$\text{Al}_n(\text{OH})_m\text{Cl}_{3n-m}$	Solution or powder	acidic
Ferric sulfate	$\text{Fe}_2(\text{SO}_4)_3 \cdot 9\text{H}_2\text{O}$	Small crystals	acidic
Ferris chloride	$\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$	Lumps or solution	acidic
Ferrous sulfate	$\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$	Small crystals	acidic

2. Coagulation chemistry:

If **Alum** is used the following reactions occur:

- $\text{Al}_2(\text{SO}_4)_3 \cdot 14\text{H}_2\text{O} \leftrightarrow 2\text{Al}^{3+} + 3\text{SO}_4^{2-} + 14\text{H}_2\text{O}$
- $2\text{Al}^{3+} + \text{colloids} \leftrightarrow \text{neutralize surface charge}$
- $2\text{Al}^{3+} + 6\text{HCO}_3^- \leftrightarrow 2\text{Al}(\text{OH})_3(\text{s}) + 6\text{CO}_2$
- If insufficient bicarbonate is available:
$$\text{Al}_2(\text{SO}_4)_3 \cdot 14\text{H}_2\text{O} \leftrightarrow 2\text{Al}(\text{OH})_3(\text{s}) + 3\text{H}_2\text{SO}_4 + 14\text{H}_2\text{O}$$
- Optimum pH: 5.5 to 6.5
- Operating pH: 5 to 8
- Since the coagulation reaction results in the decrease of the pH, so
- It is a common practice to add lime (**$\text{Ca}(\text{OH})_2$**) together with the coagulant to increase the pH **consequently countering the effect of pH decrease.**

3. Factors affecting Coagulation

The two main factors affecting the coagulation process are:

- Coagulant dosage
- pH of the water

The optimum dosage and optimum pH are determined by laboratory test called the Jar Test. the Jar test consists of six beakers filled with the water to be treated and then each is mixed and flocculated uniformly. A test is often conducted by first dosing each jar with the same value of coagulant and varying the pH of each jar. The test can then be repeated by holding the pH constant and varying the coagulant dosage.

Figure (3.4) illustrates the jar test.

Figure(3.5) illustrates the effect of dosage and pH on the coagulation process.



Figure (3.4) The Jar Test

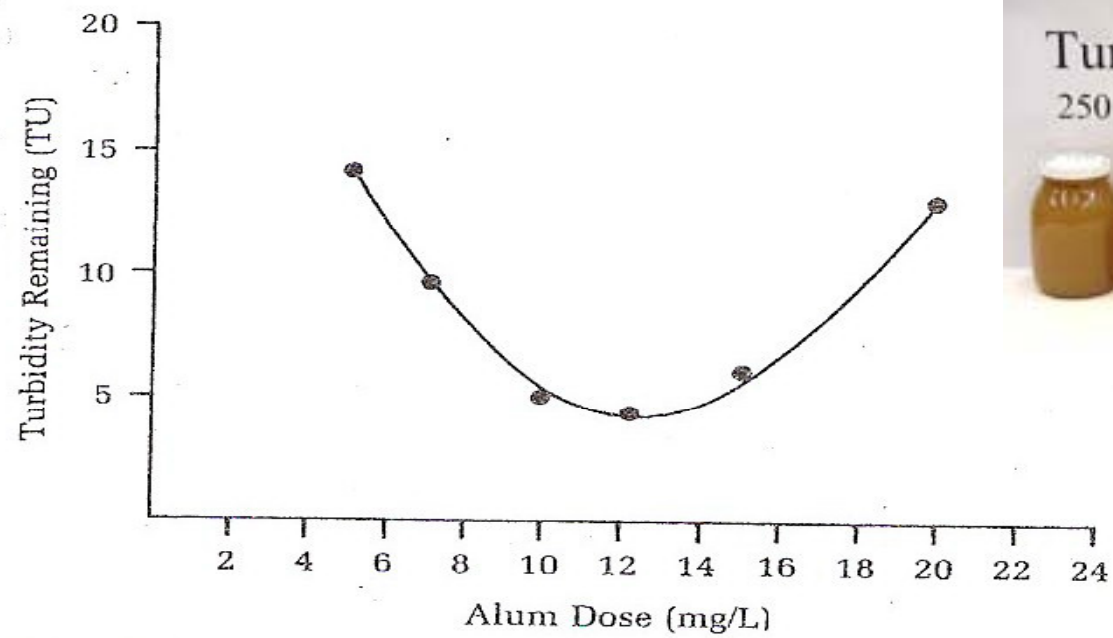
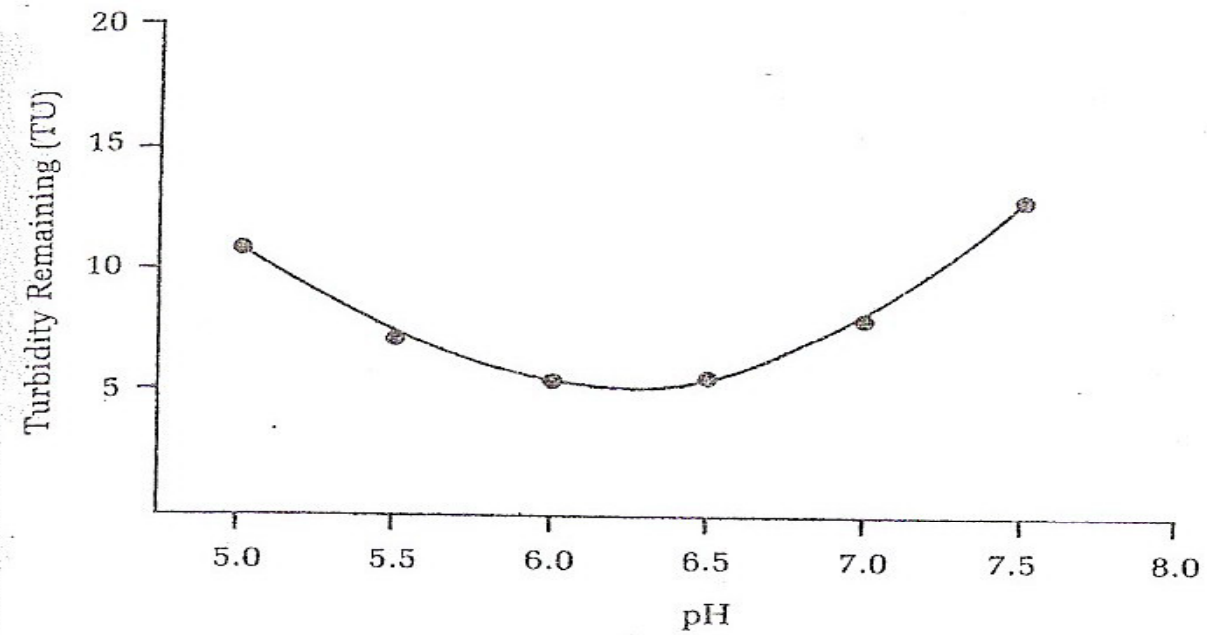


Figure 3.5:
Effect of coagulant dosage and pH on the coagulation process

4. Design of Coagulation tank:

- A. As illustrated previously, coagulation requires the addition of a chemical called “ coagulant. The coagulant should be very well mixed with water to produce homogeneous mixture of the influent water and the coagulant to achieve the best coagulation efficiency.
- B. This mixing is achieved in a tank called **Rapid mixer**. Figures 3.6 and 3.7 illustrate the geometry of the rapid mixer. It usually has a square or circular cross section to achieve best mixing efficiency.
- C. The most common mixers used in the coagulation tank are mechanical mixers. The most common types are : turbine, propeller, and paddle mixers. Figure 3.8 illustrates these types.

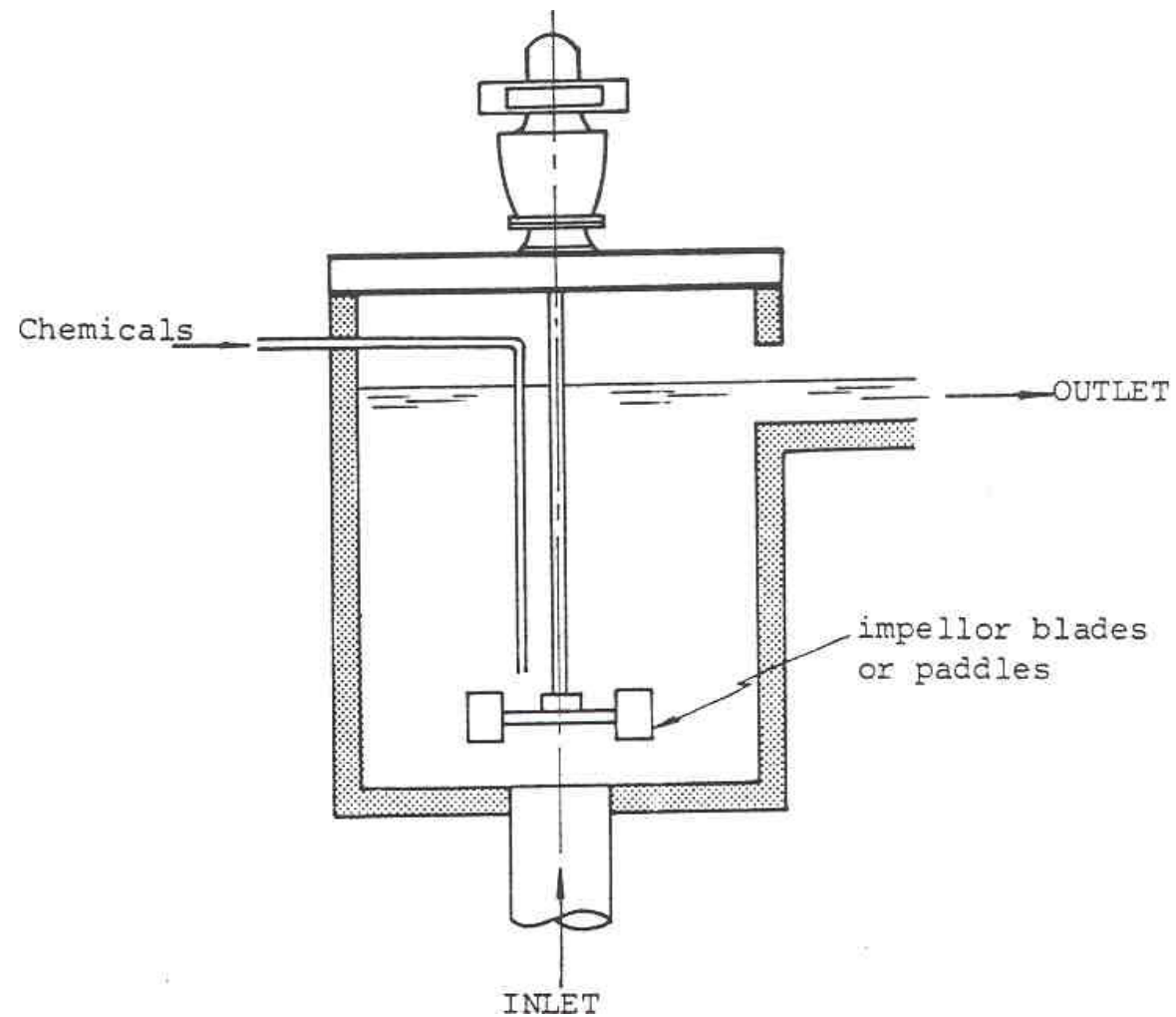


Figure 3.6 : Rapid mixer

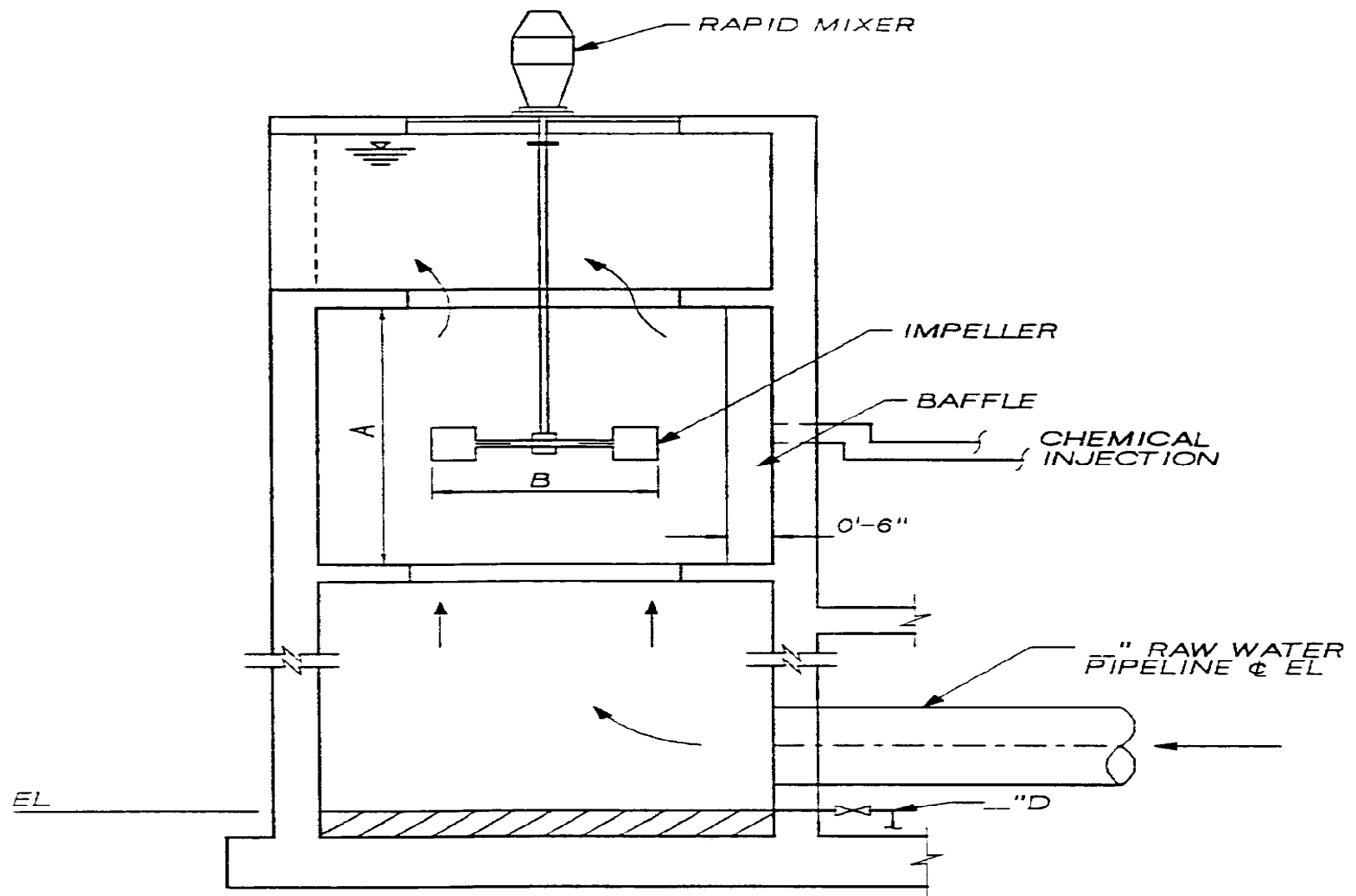
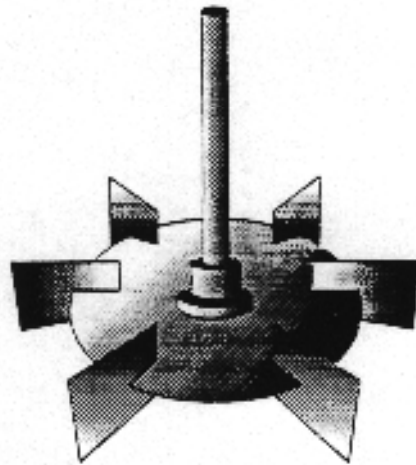


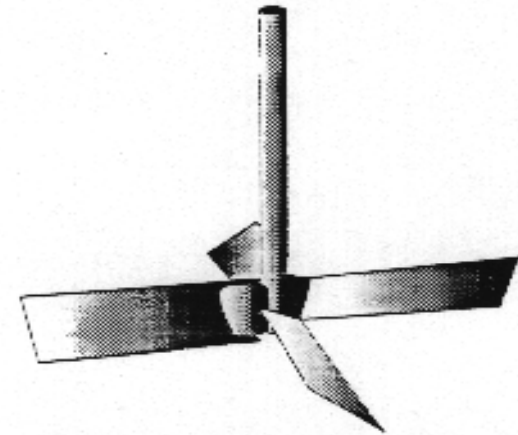
Figure 3.7 : Rapid mixer



Propeller (axial)



Disk (Rushton) Turbine (Radial)



Pitched Blade Turbine (axial)

Figure 3.8 : types mechanical rapid mixer

D. Sizing the coagulations **Rapid mixer tank:**

i. Tank Volume:

$$V = Q \cdot t$$

Where,

V = tank volume , m³

Q = design flow , m³/S

t = detention time in the tank, S

The detention time in the rapid mixer is in the range of 20-60 seconds. This short time is enough to achieve complete mixing of the coagulant and to complete the coagulation process. The water **depth** is usually taken as **1.5 times the width** of the tank if it is square or the **diameter** if it is a circular.

ii. Power Requirements:

$$P = \mu V G^2$$

Where,

P = power transmitted to the water by the mixer, N.m/s (Watt)

V = tank volume, m³

G = velocity gradient, S⁻¹

μ = dynamic viscosity of water, N.s/m²

The velocity gradient is defined as the relative velocity between two colloidal particles in water divided by the distance between them. For example, if two particles are 1 cm apart and the relative velocity between them is 10 m/s, then

$$G = 10 \text{ (mps)}/0.01\text{m} = 1000 \text{ mps/m} = 1000 \text{ S}^{-1}$$

Typical values of G in coagulation rapid mixing are given in the following Table.

Typical design values of the G for coagulation

Detention time (Seconds)	G mps/m, or S ⁻¹
20	1000
30	900
40	790
50 or more	700

Example:

A rapid mixer is to be used for coagulation of surface water with high turbidity. If the flow is 720 m³/h find the volume and dimensions of the tank and the power requirements. Assume that the detention time is 20 seconds and G=1000 S⁻¹, $\mu = 1.518 \times 10^{-3}$ N.m/s² at 5 °C.

Solution:

$$Q = 720 \text{ m}^3/\text{h} = 0.20 \text{ m}^3/\text{s}$$

$$V = 30 \times 0.2 = 6 \text{ m}^3$$

Assume the tank cross section is square ,then $V = W \times W \times 1.5W = 1.5 W^3$
 $6 = 1.5W^3$, $W = 1.587 \text{ m}$, $d = 1.5 \times 1.587 = 2.38 \text{ m}$.

$$P = \mu V G^2 = 1.518 \times 10^{-3} \times 6 \times 1000^2 = 9522 \text{ Watt} = 9.522 \text{ Kw}$$

3.5 Flocculation

1. Configurations of Flocculation tanks:

- ☐ The most common types of Flocculator are paddle and walking beam Flocculator. Figures 3.9 through 3.16 illustrate these types.
- ☐ Another type of tanks combine between flocculation and sedimentation in one tank and called solid contact Flocculator Clarifier. See Figures 3.17 and 3.18.
- ☐ Figures 3.19 and 3.20 illustrate the layout of a water treatment plant with coagulation, flocculation and sedimentation tanks .

2. Design of Flocculation tanks:

i. Tank Volume:

$$V = Q \cdot t$$

Where,

V = tank volume , m^3

Q = design flow , m^3/S

t = detention time in the tank, S

The detention time in the flocculation tank is much higher than that in the rapid mixer. It is in the range of 20-60 minutes.

ii. Power Requirements:

$$P = \mu V G^2$$

Where,

P = power transmitted to the water by the mixer, N.m/s (Watt)

V = tank volume, m^3

G = velocity gradient, S^{-1}

μ = dynamic viscosity of water, $N.s/m^2$

- The value of $G \cdot t$ is an important factor in the Flocculator. It has a range Of 10^4 to 10^5 . typical values of G is 15 to 60 S^{-1} .
- In paddle Flocculator, we usually use three compartments in series and G is tapered gradually from the first to the third compartment. For example $G_1 = 60 S^{-1}$, $G_2 = 60 S^{-1}$, $G_3 = 60 S^{-1}$. The average of the three values should be in the Above mentioned range for G . Tapering is needed to prevent the destruction of the growing flocks

The power is also expressed in terms of the paddle mixer properties as the following:

$$P = \frac{C_D A_p \rho v_p^3}{2}$$

Where,

C_D = Drag coefficient, function of paddle blades dimensions, L/W (see the table)

A_p = Area of the paddle blades, m^2

ρ = Water density, kg/m^3

v_p = velocity of the paddle relative to the water, m/s .

If more than one blade is used on the paddle the power is expressed as:

$$P = \frac{C_D \rho (A_{p1} v_{p1}^3 + A_{p2} v_{p2}^3 + A_{p3} v_{p3}^3)}{2}$$

Values of the drag coefficient for paddle-Wheel Flocculator

Length to width ration (L/W)	C _D
5	1.20
20	1.50
∞	1.90

The relative velocity (v_p) is related to the rotational speed of the paddles
By the following relation:

$$v_p = 0.75(\pi D \omega) = 0.75v_t$$

Where,

D = the distance between the center lines of the two corresponding blades on the paddle, m, (see figure 3.9, the distances D_1 , D_2 , D_3)

ω = rotational speed of the paddle, rev/s.

v_t = tangential velocity of the blade.

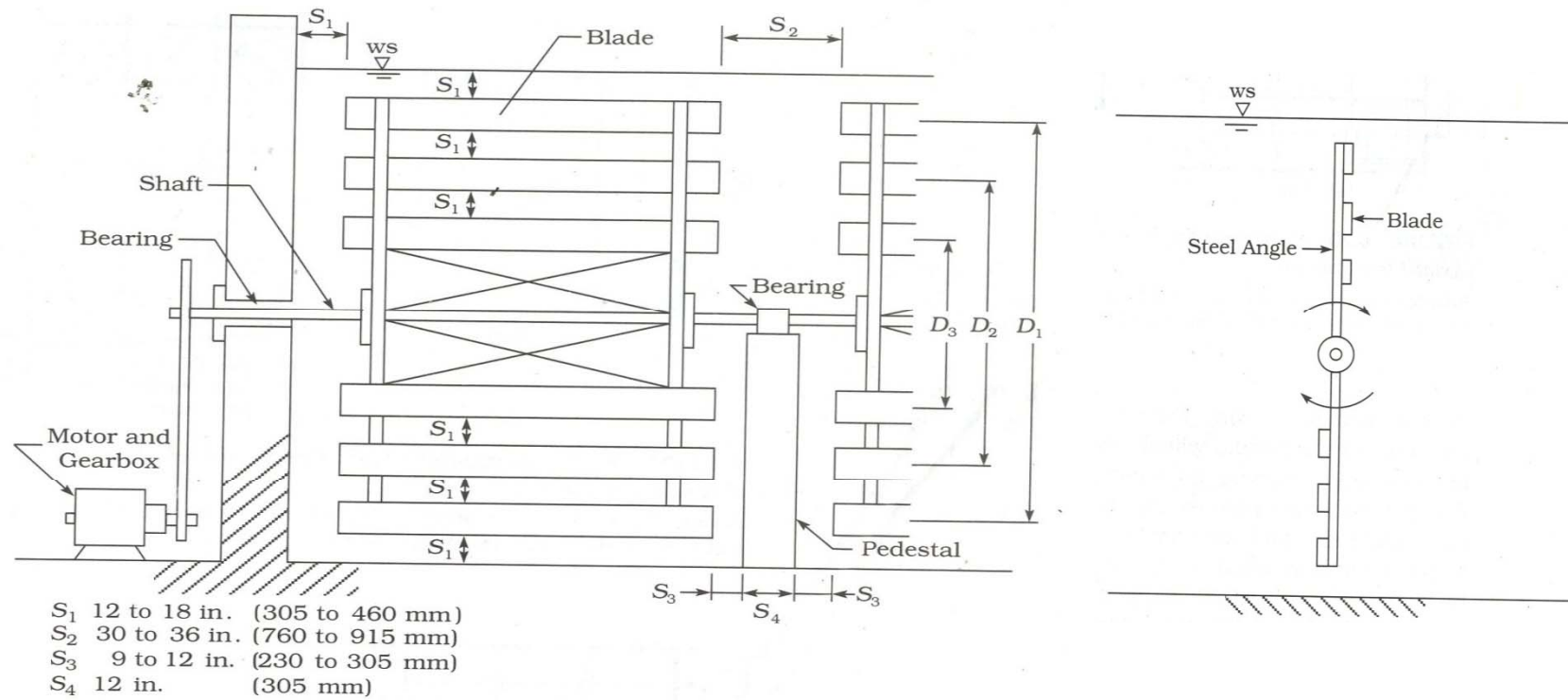


Figure 3.9: Baddel Flocculator, Horizontal Shaft

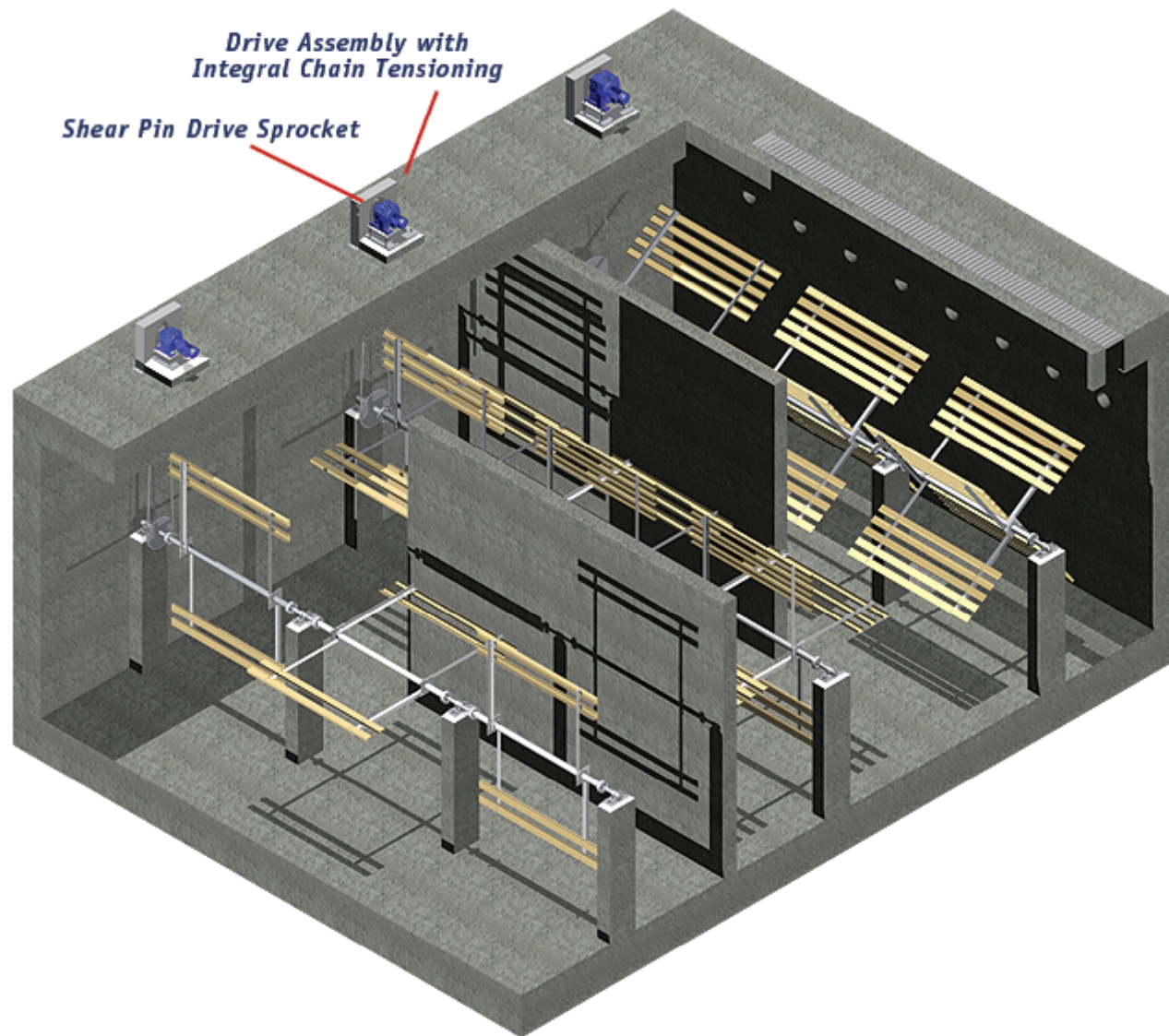


Figure 3.10 : Horizontal-Shaft Paddle Flocculator, Axial flow pattern

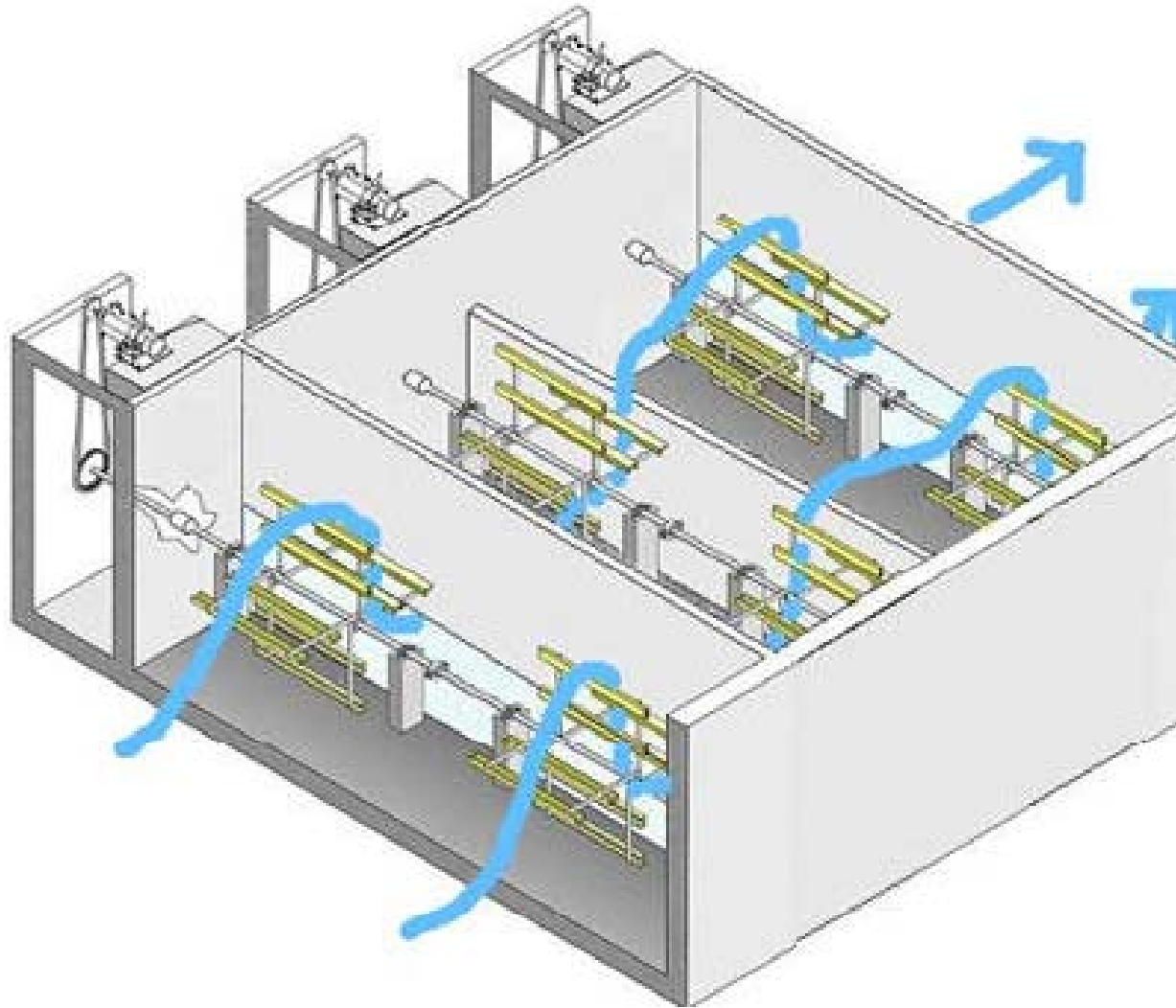


Figure 3.11: Horizontal-Shaft Paddle Flocculator, Cross flow pattern



Figure 3.12: Horizontal-Shaft Paddle Flocculator, Cross flow pattern

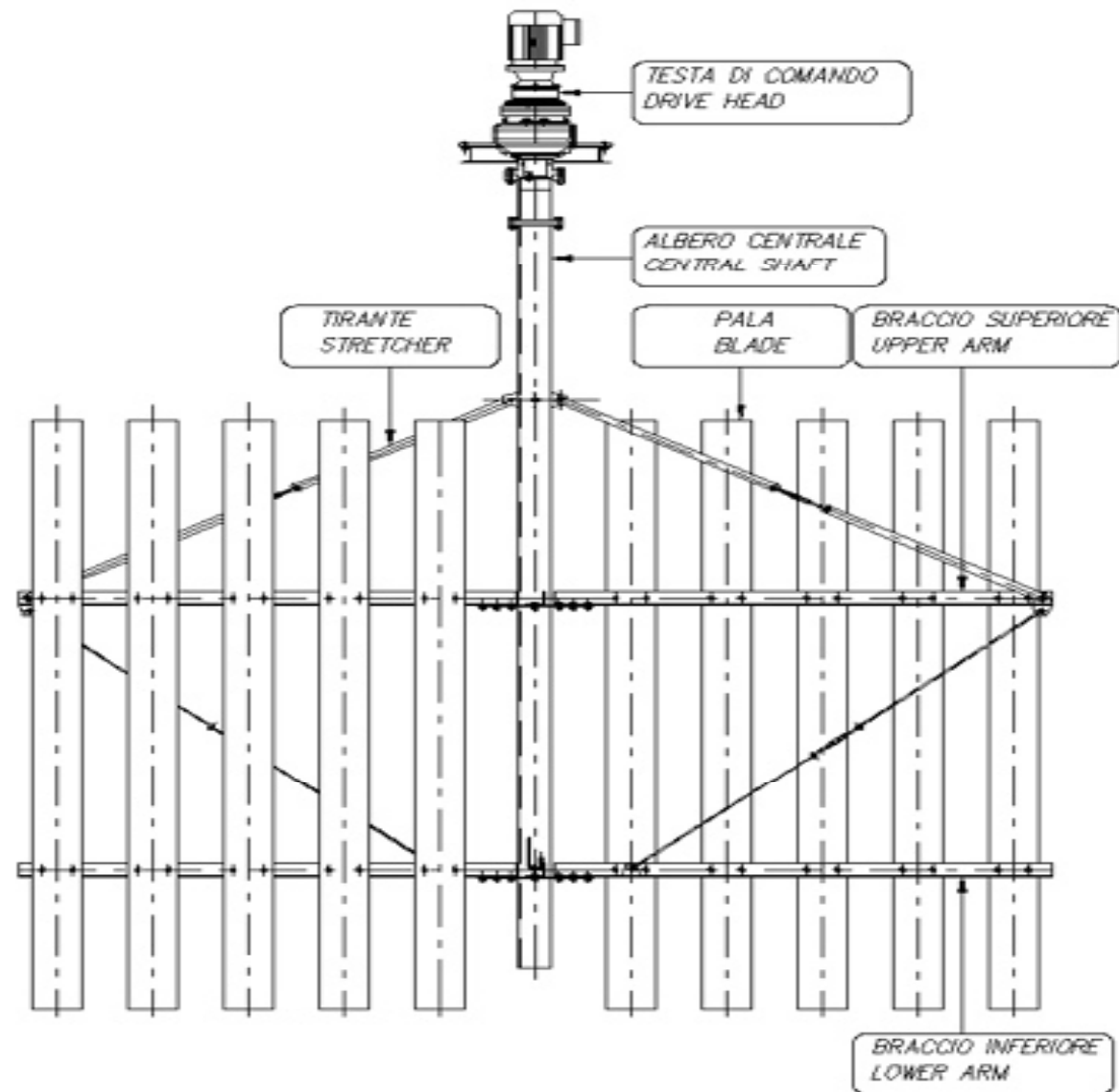


Figure 3.13: Vertical Shaft Baddel Flocculator

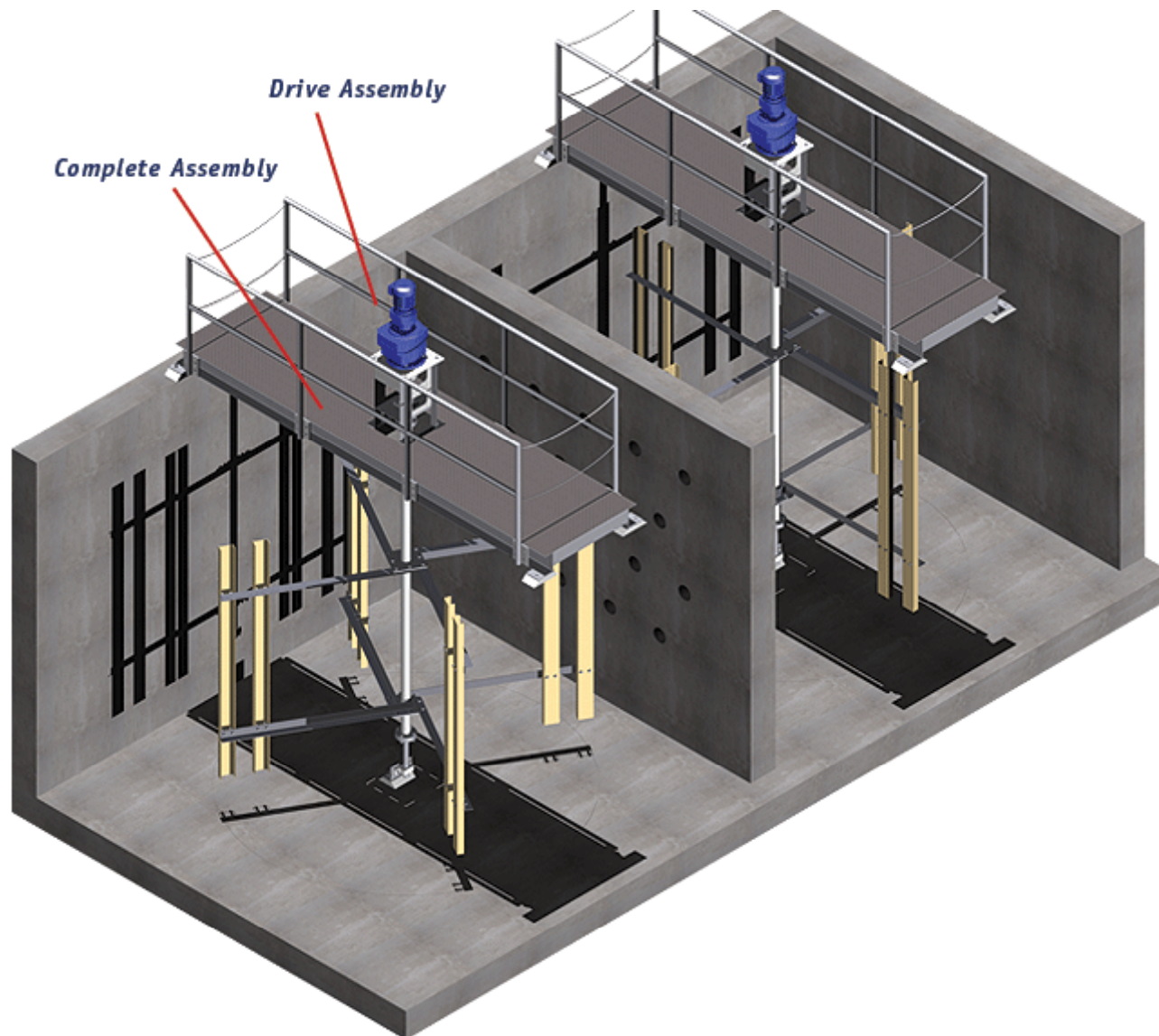


Figure 3.14: Vertical-Shaft Paddle Flocculator

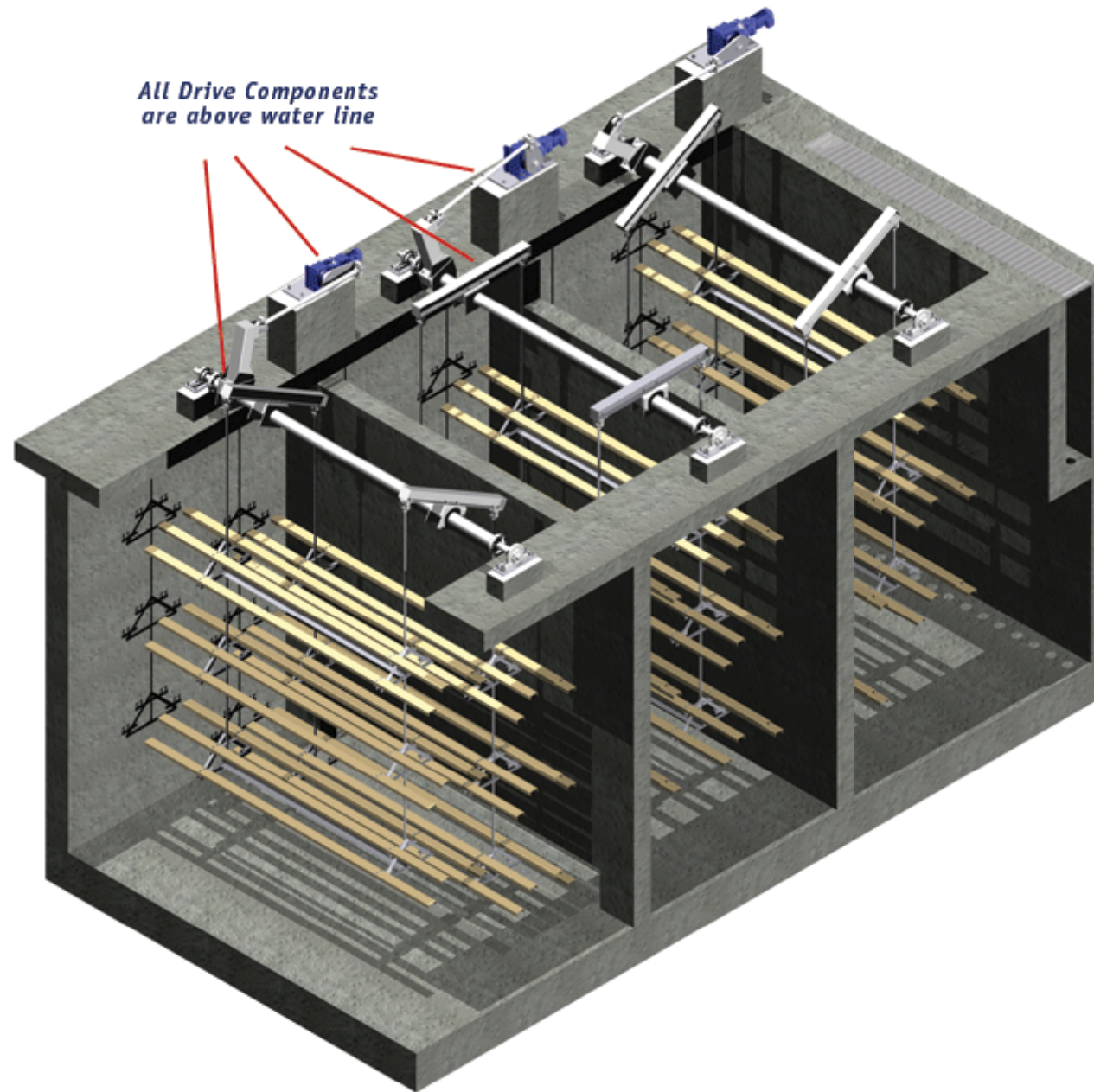


Figure 3.15: Walking Beam-Shaft addle Flocculator

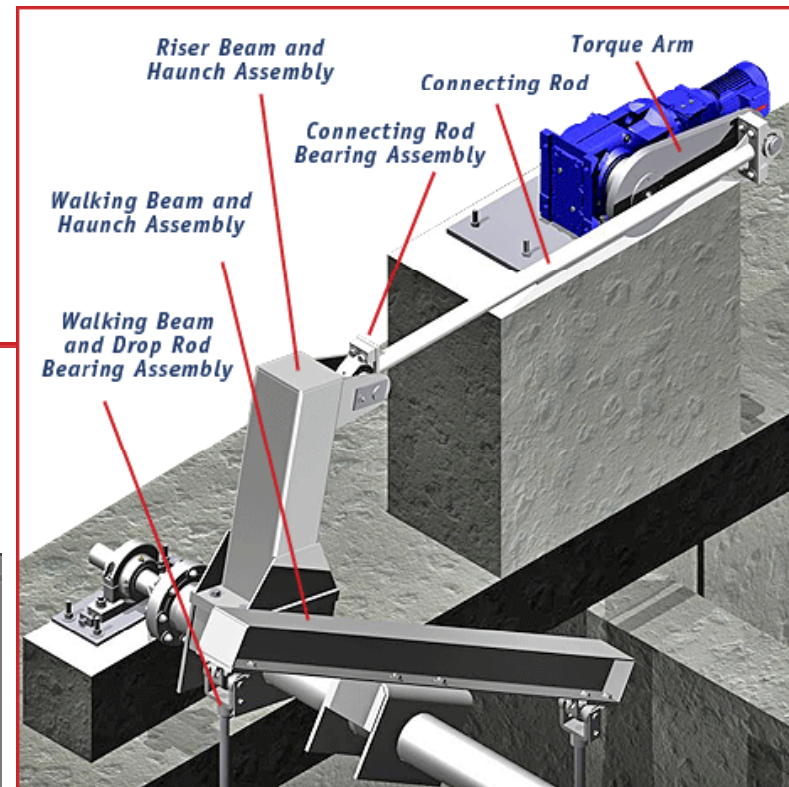
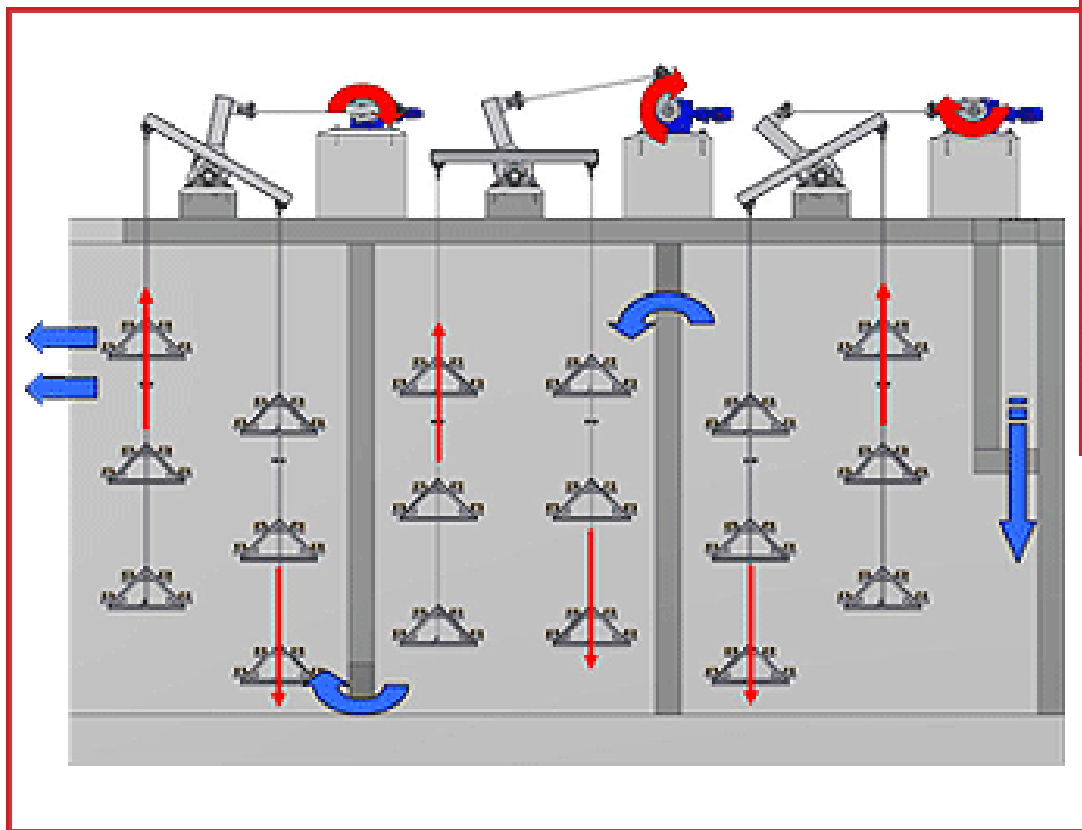


Figure 3.16 : Walking Beam Flocculator

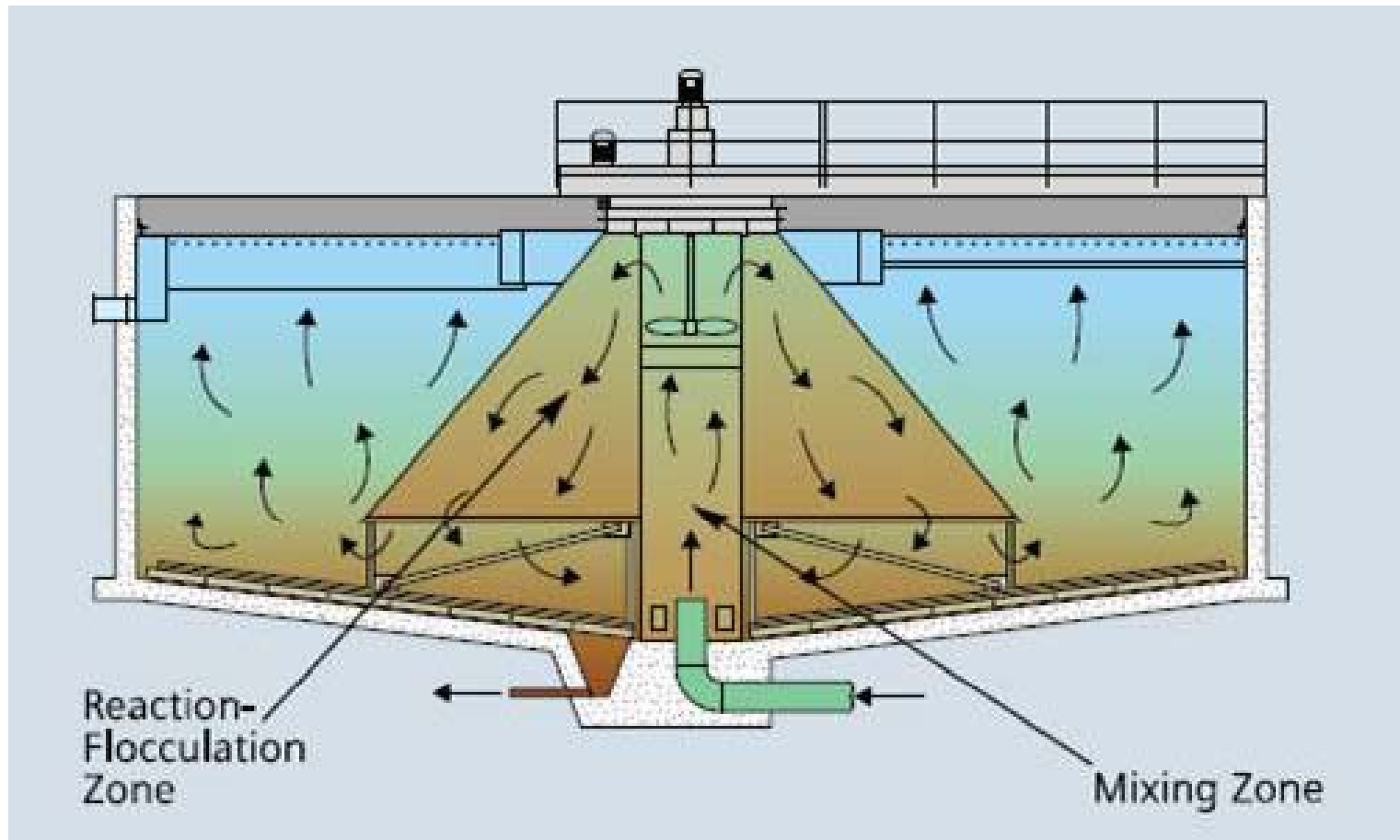


Figure 3.17a : Solids Contact Flocculator Clarifier

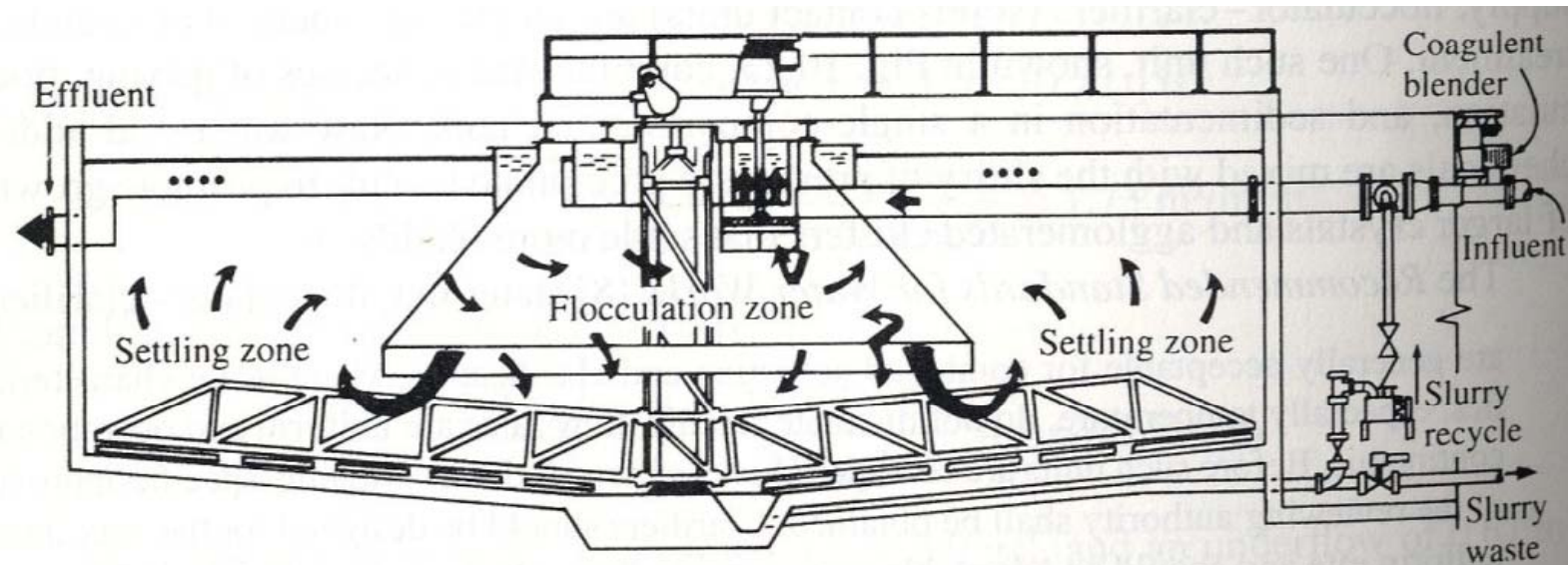


Figure 3.17 b: Solids Contact Flocculator Clarifier



Figure 3.18 : Solids Contact Flocculator Clarifier

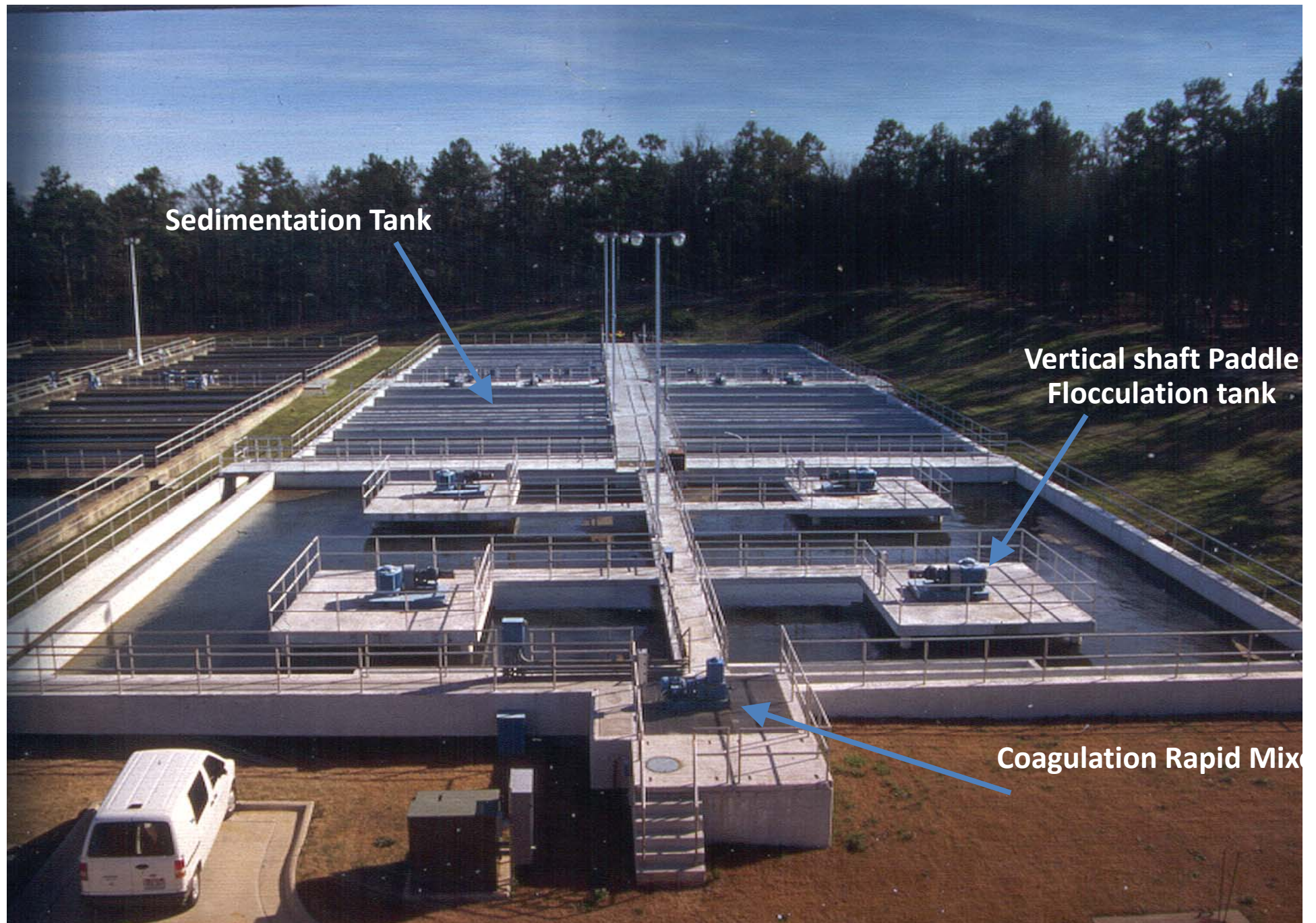


Figure 3.19 : Layout of Coagulation Rapid mixer, flocculation and sedimentation Tanks

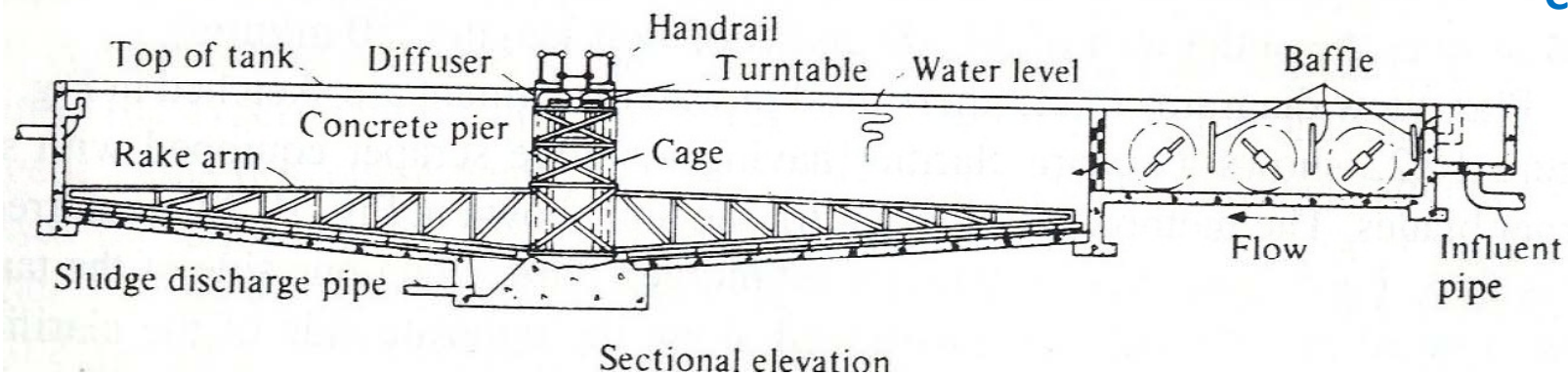
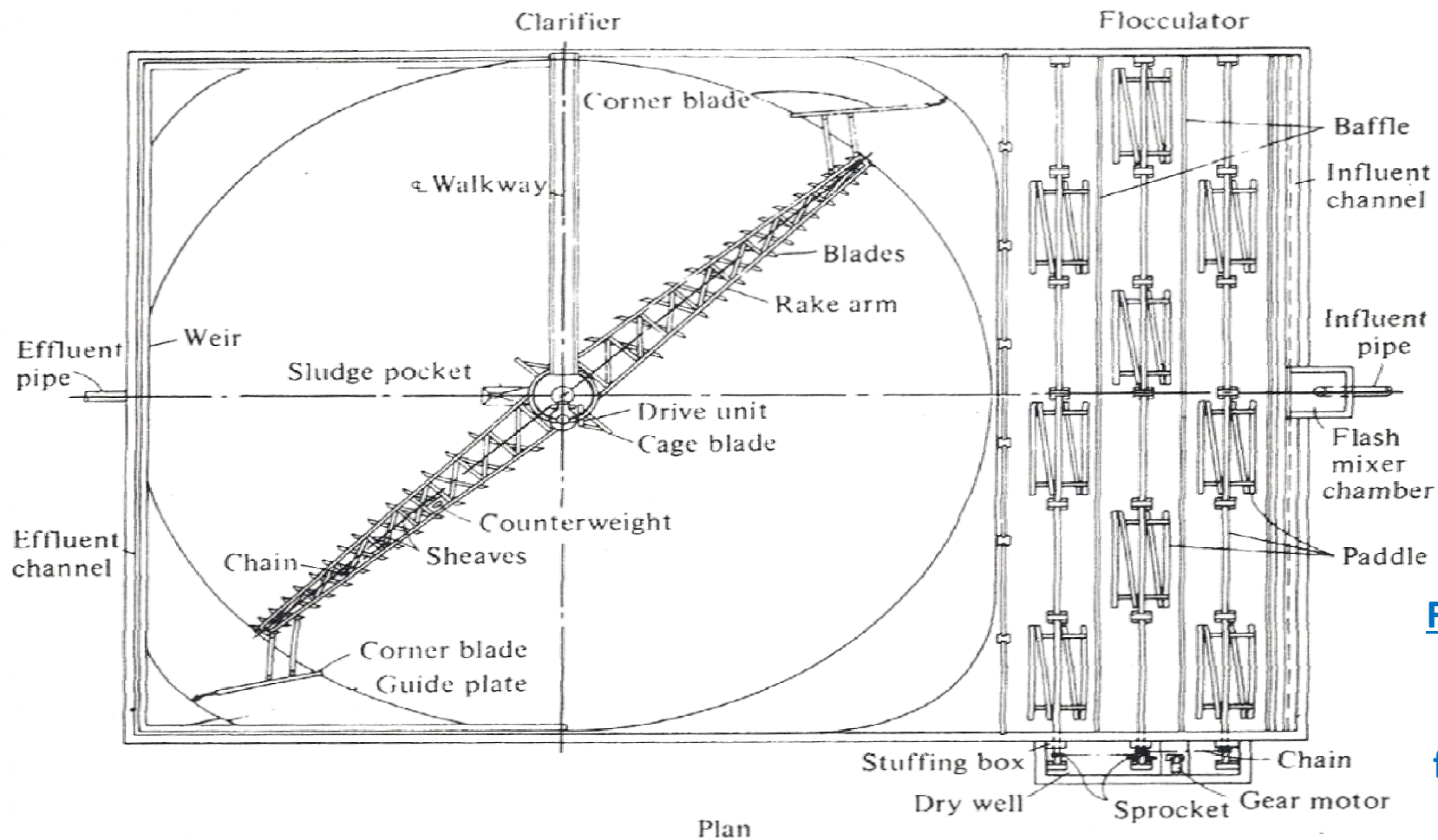


Figure 3.20 :
Layout of
Rapid mix,
flocculation
and
Clarification
Tanks

Example 1: Designing a flocculator A water-treatment plant is being designed to process $50,000 \text{ m}^3/\text{d}$ of water. Jar testing and pilot-plant analysis indicate that an alum dosage of 40 mg/L with flocculation at a Gt value of 4.0×10^4 produces optimal results at the expected water temperatures of 15°C . Determine:

1. The monthly alum requirement.
2. The flocculation basin dimensions if three cross-flow horizontal paddles are to be used.
The flocculator should be a maximum of 12 m wide and 5 m deep in order to connect appropriately with the settling basin.
3. The power requirement.
4. The paddle configuration.

SOLUTION

1. Monthly alum requirements:

$$40 \text{ mg/L} = 0.04 \text{ kg/m}^3$$

and

$$\frac{0.04 \text{ kg}}{\text{m}^3} \times 50,000 \frac{\text{m}^3}{\text{d}} \times 30 \text{ d/mo} = 60,000 \text{ kg/mo}$$

2. Basin dimensions:

a. Assume an average G value of 30 s^{-1}

$$Gt = 4.0 \times 10^4$$

$$t = \frac{4.0 \times 10^4}{30} \frac{1 \text{ min}}{60 \text{ s}}$$

$$t = 22.22 \text{ min}$$

b. Volume of the tank is

$$\begin{aligned} V &= Qt = 50,000 \text{ m}^3/\text{d} \times 22.22 \text{ min} \times 1 \text{ d}/1440 \text{ min} \\ &= 771.5 \text{ m}^3 \end{aligned}$$

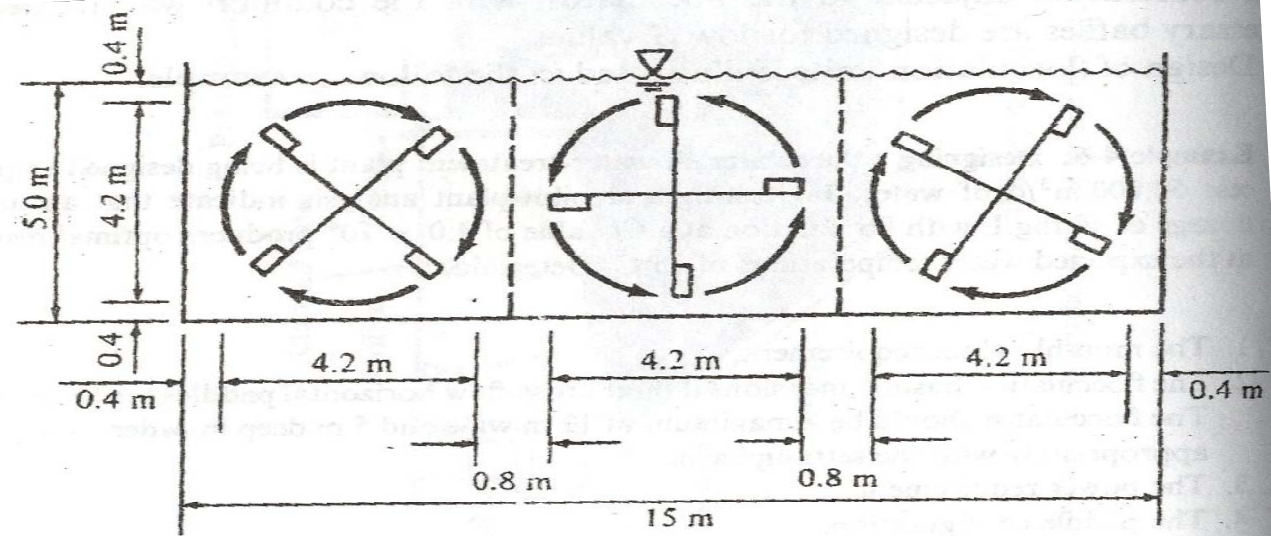
c. The tank will contain three cross-flow paddles, so its length will be divided into three compartments. For equal distribution of velocity gradients, the end area of each compartment should be square, i.e., depth equals $\frac{1}{3}$ length. Assuming maximum depth of 5 m, length is

$$3 \times 5 = 15 \text{ m}$$

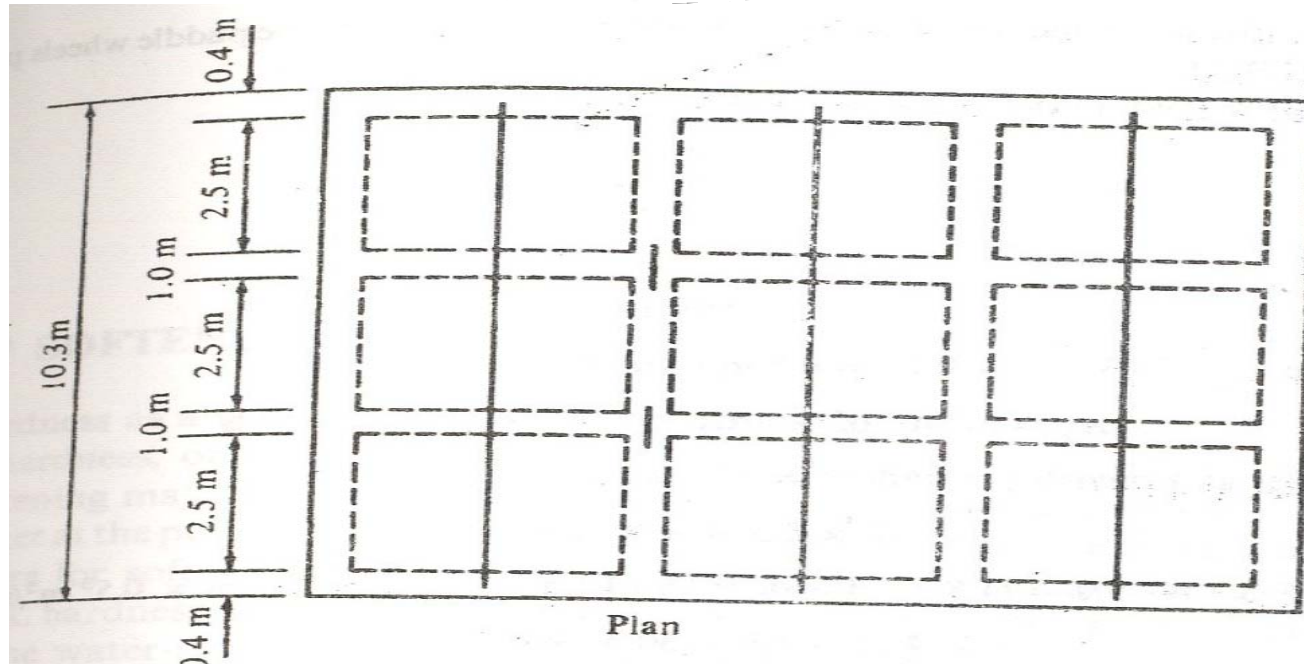
and width is

$$5 \times 15 \times w = 771.5$$

$$w = 10.3 \text{ m}$$



Profile



Plan

Each paddle wheel has four boards 2.5 m long and w wide—three paddle wheels per compartment.

- b. Calculate w from power input and paddle velocity.

$$P = \frac{C_D A_p \rho v_p^3}{2}$$

At 15°C

$$\rho = 999.1 \text{ kg/m}^3$$

Assume $v_p = 0.67 \text{ m/s} \times 0.75 = 0.5 \text{ m/s}$ and $C_D = 1.8$.

$A_p = \text{length of boards} \times w \times \text{number of boards}$

3 paddles at 4 boards per paddle = 12 boards

$$12 \times 2.5 \times w = 30w = A_p$$

$$P_i = 468.7 \text{ N} \cdot \text{m/s} = (1.8 \times 30w \text{ m} \times 999.1 \text{ kg/m}^3 \times \text{N} \cdot \text{s}^2/\text{kg} \cdot \text{m} \times 0.5^3 \text{ m}^3/\text{s}^3)$$

$$937.4 \text{ m} = 1.8 \times 30 \times 999.1 \times 0.5^3 w$$

$$937.4 \text{ m} = 6744w$$

$$w = 0.14 \text{ m}$$

- c. Calculate rotational speed of paddles.

First compartment:

$$V_t = \pi D \omega$$

$$= \pi(4.2)\omega$$

$$0.67 \text{ m/s} = \pi(4.2)\omega$$

$$\omega = 0.0508 \text{ rps} = 3.05 \text{ rev/min}$$

Second compartment:

$$P = 0.26 \text{ kW} \times 10^3 \frac{\text{N} \cdot \text{m/s}}{\text{kW}}$$

$$= 260 \text{ N} \cdot \text{m/s} = \frac{C_D A_p \rho v_p^3}{2}$$

$$= 1.8 (30 \times 0.14) \text{ m}^2 \times 999.1 \text{ kg/m}^3 \times \text{N} \cdot \text{s/kg} \cdot \text{m} \times v_p^3/2$$

$$260 \text{ N} \cdot \text{m/s} = 3777 \text{ N} \cdot \text{s}^2/\text{m} \times v_p^3$$

$$v_p = \left(260 \text{ N} \cdot \text{m/s} \times \frac{1 \text{ m}^2}{3777 \text{ N} \cdot \text{s}^2} \right)^{1/3}$$

$$= (0.07 \text{ m}^3/\text{s}^3)^{1/3} = 0.41 \text{ m/s}$$

$$v_t = v_p/0.75 = 0.55 \text{ m/s}$$

$$\omega = 2.5 \text{ rev/min}$$

Third compartment:

$$P_3 = 120 \text{ N} \cdot \text{m/s} = 3777 \text{ N} \cdot \text{s}^2/\text{m}^2 \times v_p^3$$

$$v_p = \left(120 \text{ N} \cdot \text{m/s} \times \frac{1 \text{ m}^2}{3777 \text{ N} \cdot \text{s}^2} \right)^{1/3}$$

$$= (0.03 \text{ m}^3/\text{s}^3)^{1/3} = 0.32 \text{ m/s}$$

$$v_t = 0.32 \text{ m/s} \times \frac{1}{0.75} = 0.42 \text{ m/s}$$

$$\omega = 1.91 \text{ rev/min}$$

Example 2:

A cross-flow, horizontal shaft, paddle-wheel flocculation basin is to be designed for a flow of $25,000 \text{ m}^3/\text{d}$, a mean velocity gradient of 26.7 s^{-1} (at 10°C), and a detention time of 45 min. The GT value should be from 50,000 to 100,000. Tapered flocculation is to be provided, and three compartments of equal depth in series are to be used, as shown in Figure 3.20. The G values determined from laboratory tests for the three compartments are $G_1 = 50 \text{ s}^{-1}$, $G_2 = 20 \text{ s}^{-1}$, and $G_3 = 10 \text{ s}^{-1}$. These give an average G value of 26.7 s^{-1} . The compartments are to be separated by slotted, redwood baffle fences, and the floor of the basin is level. The basin should be 15.0 m in width to adjoin the settling basin. The speed of the blades relative to the water is three-quarters of the peripheral blade speed. Determine:

1. The GT value.
2. The basin dimensions.
3. The paddle-wheel design.
4. The power to be imparted to the water in each compartment.
5. The rotational speed of each horizontal shaft in rpm.
6. The rotational speed range if 1:4 variable-speed drives are employed.
7. The peripheral speed of the outside paddle blades in m/s.

SOLUTION The GT value is

$$GT = \frac{26.7}{s} \left| \frac{45 \text{ min}}{60 \text{ s}} \right|$$
$$= \boxed{72,100}$$

Since the GT value is between 50,000 and 100,000, the detention time of 45 min is satisfactory. Basin volume, V , is given by

$$V = \frac{25,000 \text{ m}^3}{24 \text{ h}} \left| \frac{45 \text{ min}}{60 \text{ min}} \right|$$
$$= 781 \text{ m}^3$$

Profile area = $781 \text{ m}^3 / 15.0 \text{ m} = 52.1 \text{ m}^2$.

Assume compartments are square in profile, and x is the compartment width and depth. Thus,

$$(3x)(x) = 52.1 \text{ m}^2 \quad x^2 = 17.37 \text{ m}^2 \quad x = 4.17 \text{ m}$$

$$3x = 3(4.17 \text{ m}) = 12.51 \text{ m}$$

$$\boxed{\text{Use width} = \text{depth} = 4.17 \text{ m, length} = 12.51 \text{ m}}$$

Assume a paddle-wheel design as shown in Figure 3.9 with $D_1 = 3.35$ m, $D_2 = 2.44$ m, and $D_3 = 1.52$ m. Use four paddle wheels per shaft, and assume the blades are 15 cm wide and 3.00 m long.

$$\begin{aligned}\text{Blade area per shaft} &= (0.15 \text{ m})(3.00 \text{ m})(6)(4) \\ &= 10.8 \text{ m}^2\end{aligned}$$

$$\begin{aligned}\text{Percent of cross-sectional area} &= \frac{10.8}{15} \times \frac{100}{4.17} \\ &= 17.3\%\end{aligned}$$

Since this is between 15 to 20%, make the trial design using the assumed paddle-wheel design. The power, P , is given by

$$G = \sqrt{\frac{P}{\mu V}} \quad \text{or} \quad P = \mu G^2 V$$

Absolute viscosity, μ , at 10°C is 0.00131 N-s/m²; thus the power for the first compartment is

$$\begin{aligned}P &= \frac{0.00131 \text{ N-s}}{\text{m}^2} \times \frac{(50)^2}{\text{s}^2} \times \frac{783 \text{ m}^3}{3} \\ &= 855 \text{ N-m/s} = 855 \text{ J/s} = 855 \text{ W}\end{aligned}$$

Power per wheel = $(855 \text{ N-m/s})^{1/4} = 214 \text{ N-m/s}$

$$P = \frac{C_D A_p \rho v_p^3}{2}$$

The length-width ratio is $3.0/0.15 = 20$; thus $C_D = 1.50$.

The blade velocity relative to water is

$$v_p = 0.75(\pi D \omega)$$

Thus,

$$v_{p1} = 0.75 * 3.14 * 3.35 \omega = 7.893 \omega$$

In a like manner, $v_{p2} = 5.49 \omega$; $v_{p3} = 3.581 \omega$

The power per wheel is

$$P = \frac{C_D \rho (A_{p1} v_{p1}^3 + A_{p2} v_{p2}^3 + A_{p3} v_{p3}^3)}{2}$$

Since $A_1 = A_2 = A_3$, and all C_D values are equal,

$$P = \frac{C_D \rho A (v_{p1}^3 + v_{p2}^3 + v_{p3}^3)}{2}$$

or

$$214 \text{ N-m/s} = (1.5)(0.15 \text{ m})(3.0 \text{ m})(2)(999.7 \text{ kg/m}^3)(1/2)[(7.893)^3(\omega)^3 + (5.749)^3(\omega)^3 + (3.581)^3(\omega)^3] \text{ m}^3/\text{s}^3$$

$$214 \text{ N-m/s} = (674.8 \text{ kg-m}^2/\text{s}^3)(1 \text{ N-s/kg-m})(491.7 + 190.0 + 45.9)(\omega)^3$$

From this,

$$\omega = 0.076 \text{ and } \boxed{\omega = (0.076)60 = 4.55 \text{ rpm}}$$

$v_t = \pi D \omega$; thus, for the outside blade,

$$\boxed{v_t = (\pi)(3.35 \text{ m})(0.076) = 0.80 \text{ m/s}}$$

Since $v_t < 0.91 \text{ m/s}$, the design of the paddle wheels is satisfactory. The maximum rotational speed is 4.55 rpm; therefore, the minimum rotational speed = $(1/4)4.55 = 1.14 \text{ rpm}$. Thus,

$$\boxed{\text{Rotational speed for 1:4 drive} = 1.14 \text{ to } 4.55 \text{ rpm}}$$

In a like manner, the power, rotational speed, peripheral blade speed, and rotational speed range are computed for the second and third compartments. Following is a summary of the values.

First compartment:

$$\begin{aligned} P &= 855 \text{ N-m/s} = 855 \text{ J/s} = 855 \text{ W} \\ \text{rpm} &= 4.55; \text{ range} = 1.14 \text{ to } 4.55 \text{ rpm} \\ \text{m/s} &= 0.80 \end{aligned}$$

Second compartment:

$$\begin{aligned} P &= 137 \text{ N-m/s} = 137 \text{ J/s} = 137 \text{ W} \\ \text{rpm} &= 2.46; \text{ range} = 0.62 \text{ to } 2.46 \text{ rpm} \\ \text{m/s} &= 0.43 \end{aligned}$$

Third compartment:

$$\begin{aligned} P &= 34.2 \text{ N-m/s} = 34.2 \text{ J/s} = 34.2 \text{ W} \\ \text{rpm} &= 1.56; \text{ range} = 0.39 \text{ to } 1.56 \text{ rpm} \\ \text{m/s} &= 0.27 \end{aligned}$$