Cornell Engineering
Civil and Environmental Engineering

CEE 4540

Sustainable municipal drinking water treatment

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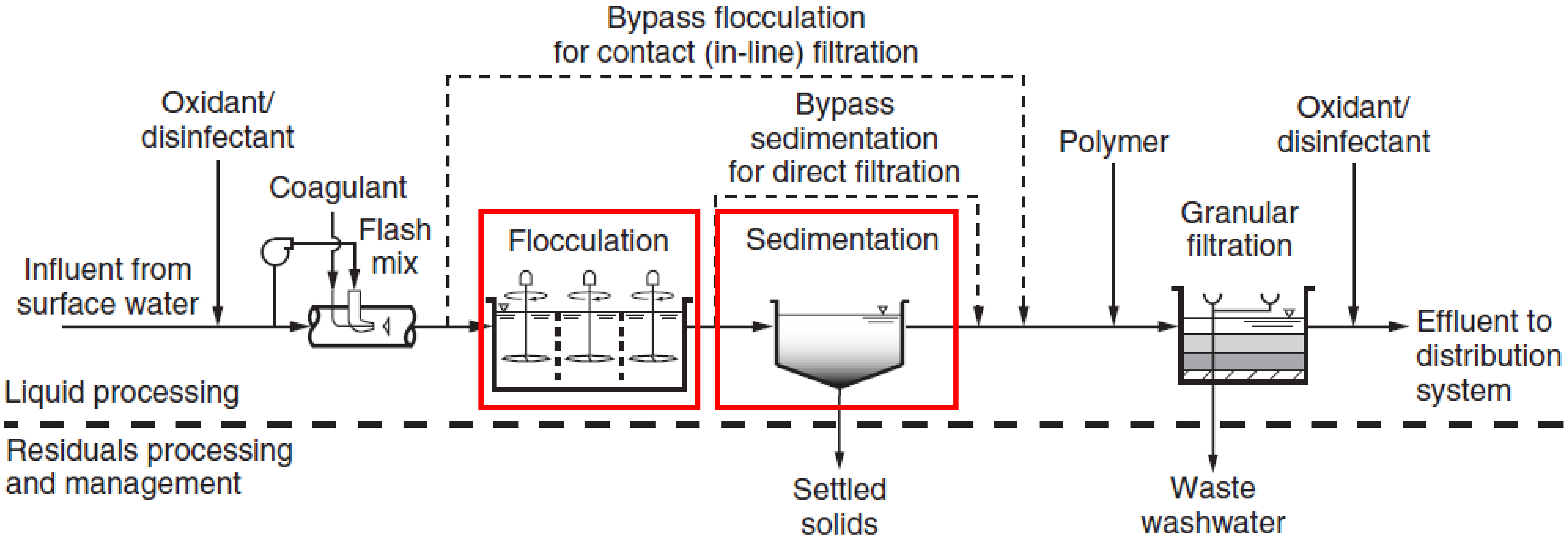
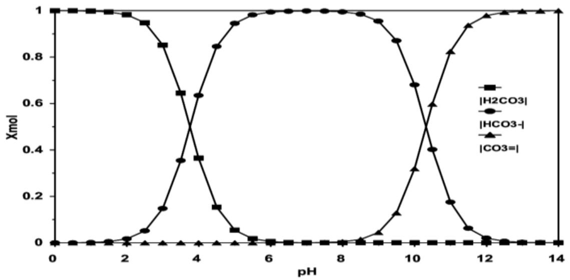
Class #4 09/10/2018 2:55 – 4:10pm

Quick Review: Intake; Screening; & Coagulation



Coagulation Type and Dosage Calculations



- Goal:
  - Form strong and settleable flocs
  - Remove enough % of Total Organic Carbon (TOC) for DBP control
- Consider the following WQ Parameters
  - Raw Water
    - Alkalinity (coagulants are usually acidic, could drive pH down and reduce H2CO3)
    - pH of finished water
    - TOC (how much TOC removal is required?)
  - Coagulated Water
    - Residual TOC level
    - Final pH may needs to be adjusted for downstream distribution system pipeline corrosion control
    - Jar testing and pilot testing are required

Jar Testing

- Establish testing matrix
  - pH range (e.g., pH 5 – pH 10)
  - Coagulant dose range (e.g., 1 ppm to 10 ppm)
  - Polymer dose range (e.g., 0.1 ppm to 1 ppm)
- Add same quantity of water to each jar (2L)
- Turn on mixer to appropriate speed
  - Single speed if just for adsorption (e.g., TOC, arsenic, etc.)
  - Adjust speed based on G-force desired at various stage
- Add coagulant and adjust pH to each jar according to testing plan

Jar Testing (continued)

- Stop the mixer
- Take water sample from different depth after certain time to measure turbidity
- Filter water sample from each jar with 0.45 micron filters
- Analyze for TOC and/or other desired water quality parameters
- Plot testing results
  - TOC vs. coagulant dose
  - TOC vs. pH
  - Turbidity vs. coagulant dose
- Determine optimal coagulation scheme

Coagulation Chemistry

- Both Ferric and Aluminum based coagulants are “acidic” and will consume the alkalinity in the water; thereby lowering pH in the treated water

$$FeCl_3 + 3H_2O \rightarrow Fe(OH)_{3\downarrow} + \underline{3H^+} + 3Cl^-$$

$$Fe_2(SO_4)_3 \cdot 9H_2O \rightarrow 2Fe(OH)_{3\downarrow} + \underline{6H^+} + 3SO_4{}^{2-} + 3H_2O \qquad (9\text{-}13)$$

$$Al_2(SO_4)_3 \cdot 14H_2O \rightarrow 2Al(OH)_{3\downarrow} + \underline{6H^+} + 3SO_4{}^{2-} + 8H_2O \qquad (9\text{-}11)$$

# of associated hydration water could change

Enhanced Coagulation

- Typical goal of coagulation is to achieve particle de-stabilization and sedimentation
- For public health protection from TTHM & HAAs, Enhanced Coagulation is required to remove certain % of TOC from the water. Coagulant dose will be higher that what's required for particle de-stabilization. Actual TOC removal % depending water alkalinity. Water with lower pH can remove more TOC, and water with lower alkalinity is easier to adjust pH lower either with acid or with coagulant itself ($FeCl_3$ and $Al_2 (SO_4)_3$ are acidic).

Table 3-3
Required Removal of Total Organic Carbon by Enhanced Coagulation and Enhanced Softening for Step 1 Compliance

Source Water TOC (*mg/L*)	Source Water Alkalinity (*mg/L* as $CaCO_3$)		
	0–60	**>60–120**	**>120**
>2.0–4.0	35.0%	25.0%	15.0%
>4.0–8.0	45.0%	35.0%	25.0%
>8.0	50.0%	40.0%	30.0%

Sludge Production

- Enhanced Coagulation could lead to additional sludge generated
- Solid calculations

Homework: Calculate solid generation from coagulation using ferric chloride

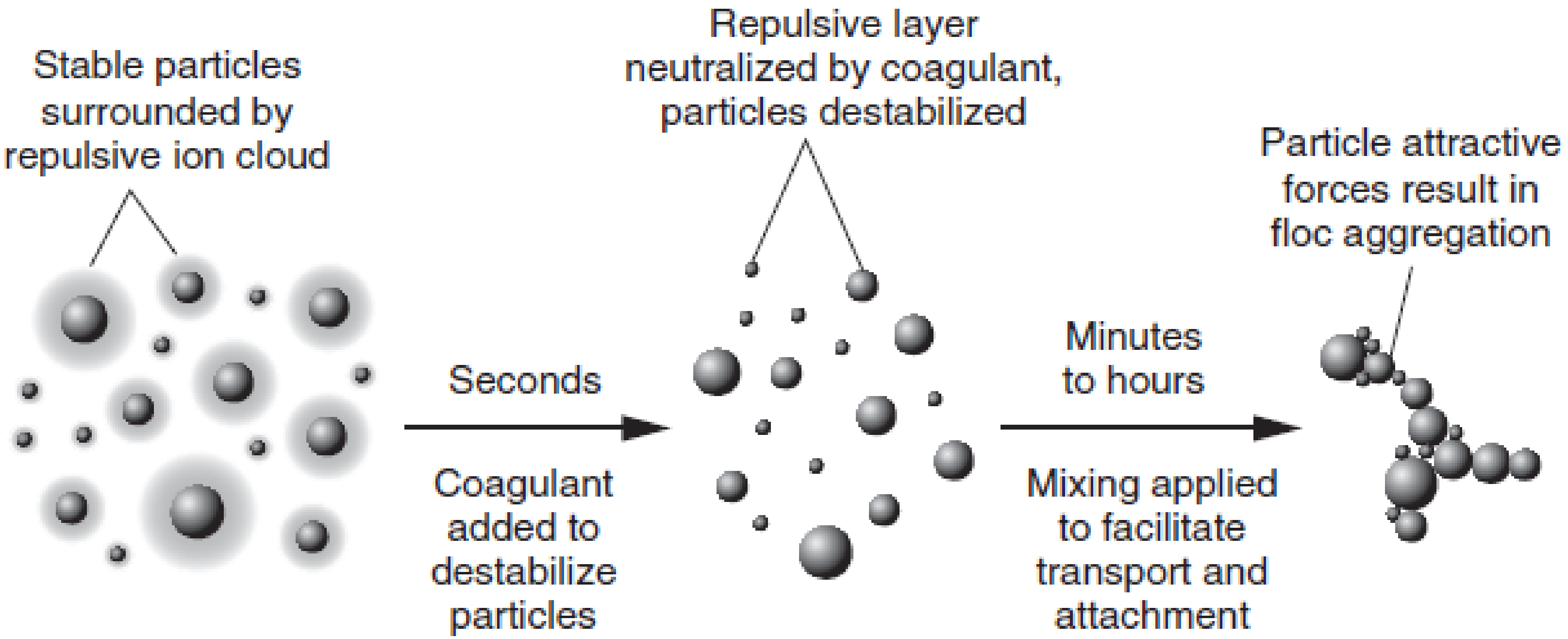
- Plant Capacity: 10 mgd
- Coagulant dose is 10 mg/L as $FeCl_3$
- Assume water content in the dewatered sludge is 75%

Q: How many lbs of dewatered solid will be generated daily?

Hint: Mwt. for Fe is 55.85 and Mwt. For Cl is 35.45. When FeCl3 is hydrolyzed ferric hydroxides solid $Fe(OH)_3$ is formed.

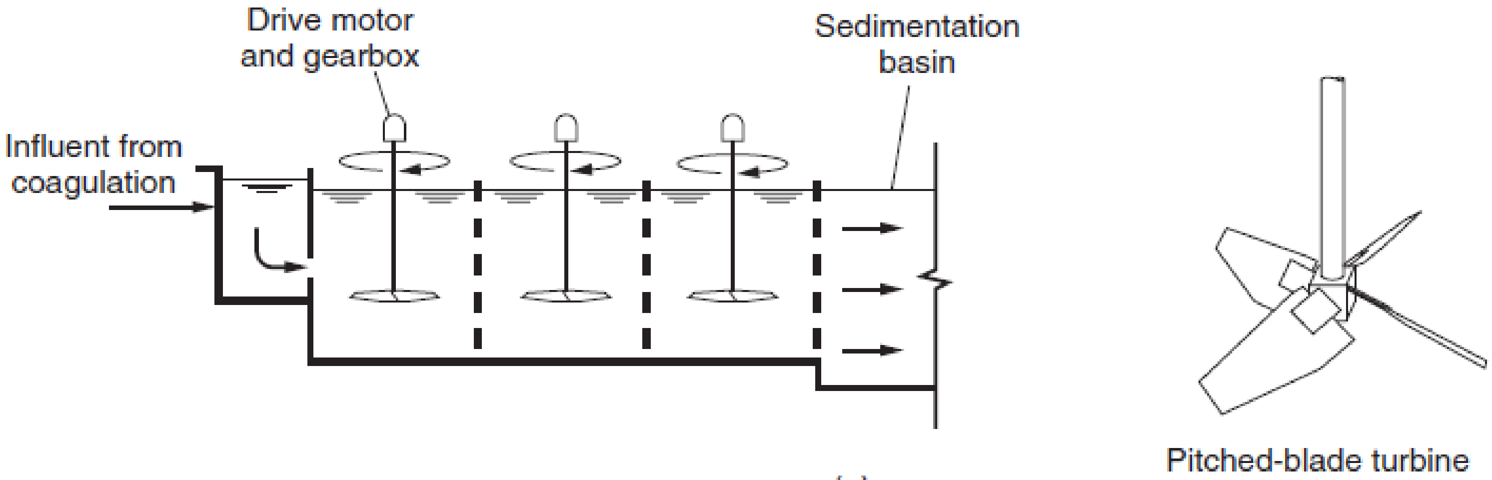
Steps of Flocculation

- Perkinetic/Microscale Flocculation (Browning Motion)
  - Aggregation of micro particles (in seconds)
- Orthokinetic/Macroscale Flocculation assisted with mixing energy

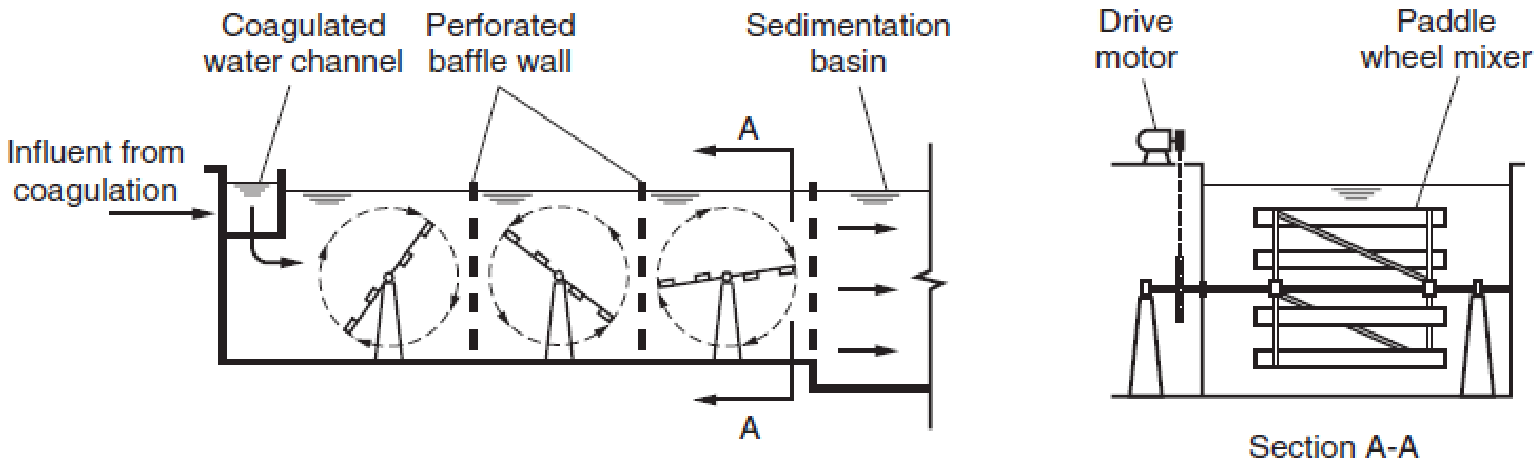


Types of Flocculators

- Mechanical

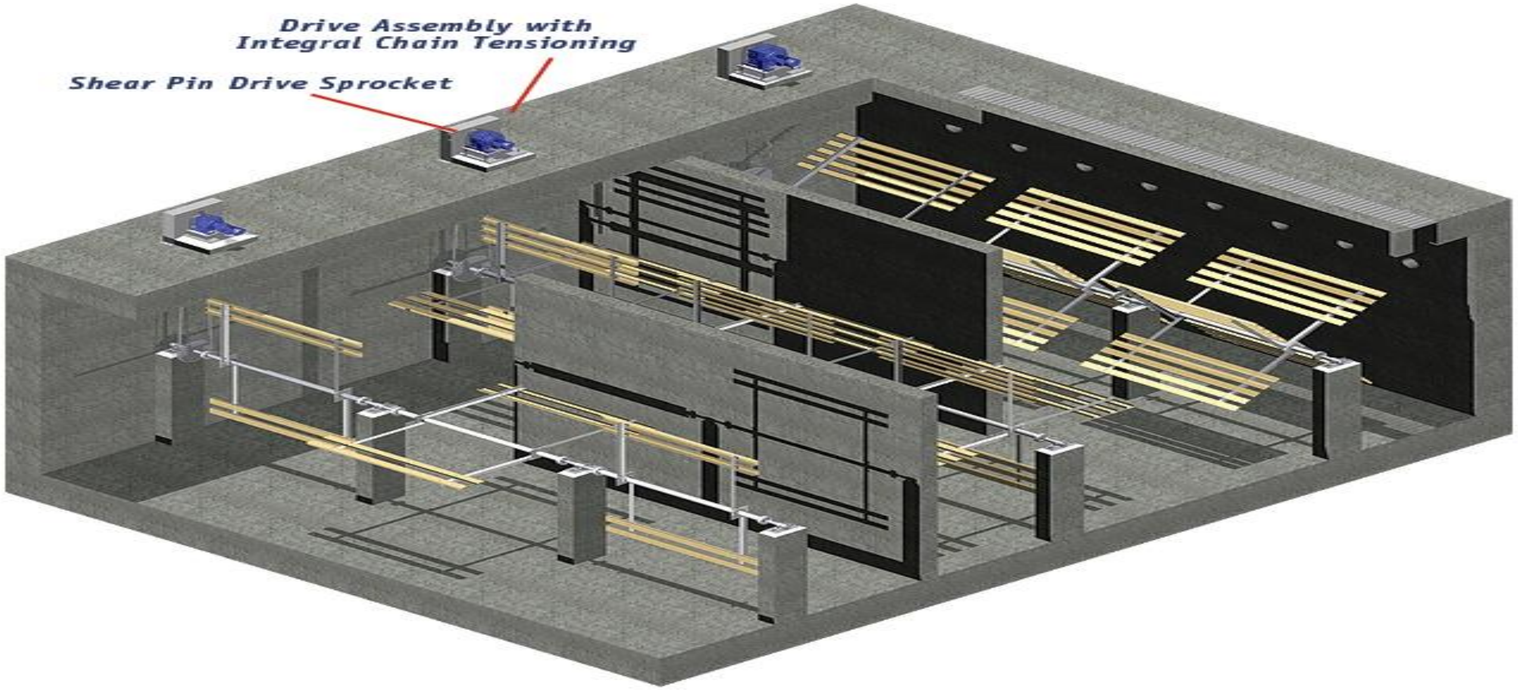


(a)



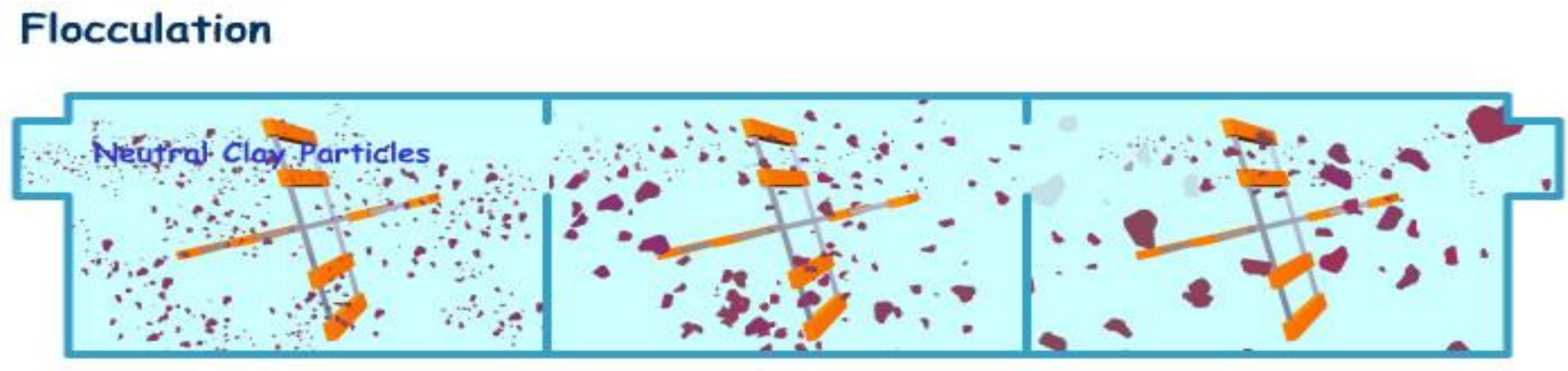
Mechanical Mixing to Facilitate Flocculation

- Agitators shall be used to assist flocculation at different stages without breaking larger flocs
- Tapered mixing speed. Driven by variable speed drives with the peripheral speed of paddles ranging from 0.5 to 3.0 feet per second; faster at the front & slower in the back



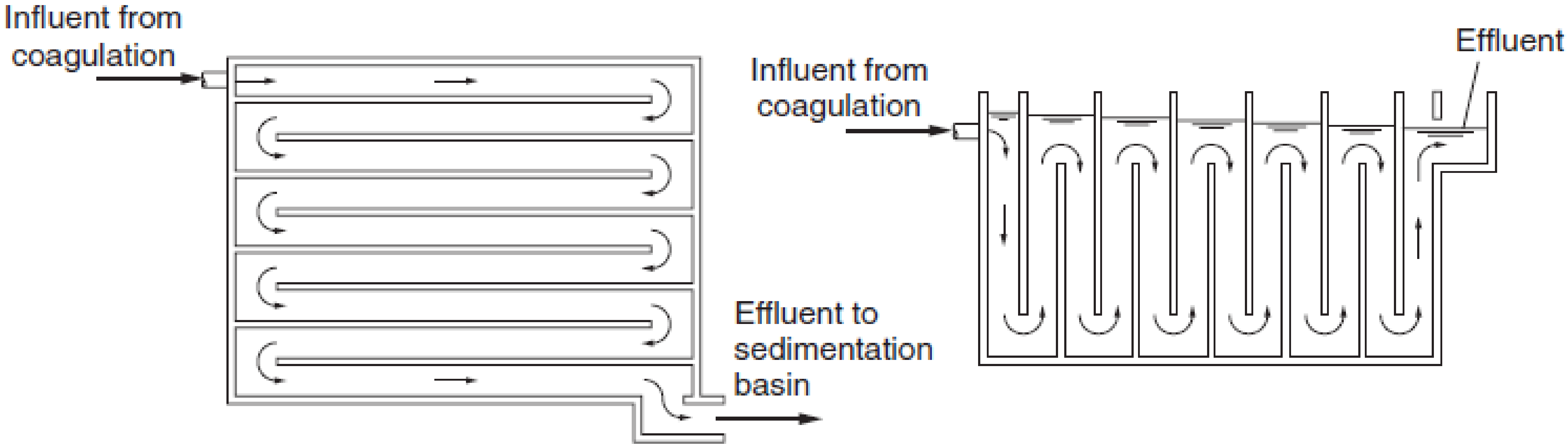
Flocculation Basin

- The flocs are getting larger and larger as it passes from stage to stage.
- The mixing intensity is generally reduced as flow passes through the compartments
- Overall detention time is around 30 min with a flow-through velocity of 0.5 – 1.5 ft/min



Types of Flocculators

– Hydraulic Flocculators

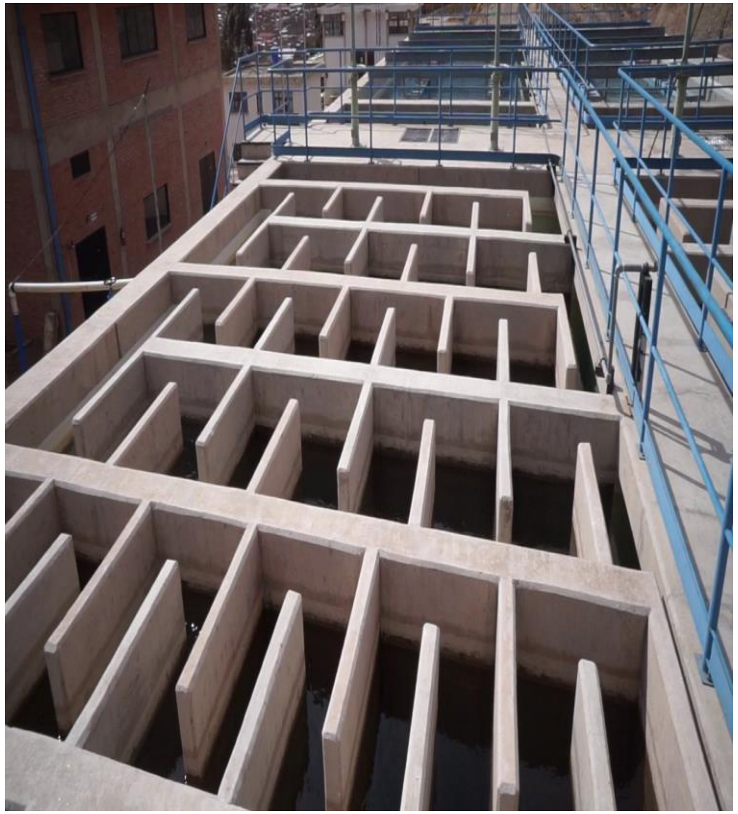


Types of Flocculators

Horizontal Shaft Flocculation

Vertical Turbine Flocculation

Hydraulic Flocculation



Selection of Proper Flocculation Approach

- Include justification in your design

Table 9-10
Comparison of basic approaches to flocculation

Process Issue	Horizontal Shaft with Paddles	Vertical-Shaft Turbines	Hydraulic Flocculation
Type of floc produced	Large and fluffy	Small to medium, dense	Very large and fluffy
Head loss	None	None	0.05–0.15 m
Operational flexibility	Good, limited to low $\overline{G}$	Excellent	Moderate to poor
Capital cost	Moderate to high	Moderate	Low to moderate
Construction difficulty	Moderate	Easy to moderate	Easy to difficult
Maintenance effort	Moderate	Low to moderate	Low to moderate
Compartmentalization	Moderate compartmentalization	Excellent compartmentalization	Excellent compartmentalization, some designs nearly plug flow

Typical design criteria for mechanical flocculators

Table 9-11
Typical design criteria for horizontal-shaft paddles and vertical-shaft turbines

Design Parameter	Unit	Horizontal Shaft with Paddles	Vertical-Shaft Turbines
Velocity gradient, $\overline{G}$	s^{-1}	5–40	10–80
Tip speed, maximum	m/s	<0.5	1–3
Rotational speed	rev/min	0.5–3	5–20
Compartment [a] dimensions (plan)			
Width	m	3–25	3–8
Length	m	3–8	3–8
Number of stages	No.	2–6	2–4
Variable-speed drives	—	Common	Common

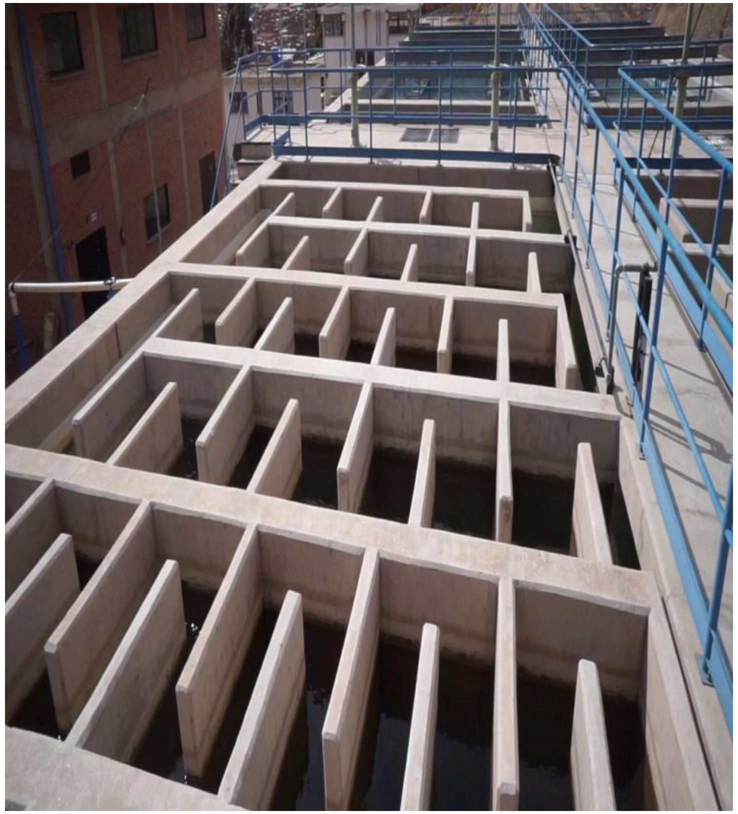
[a]The compartment is the region influenced by an individual flocculator. Horizontal-shaft flocculators often have multiple paddle wheel assemblies on a single flocculator shaft. Vertical turbine flocculators may or may not have baffle walls between the compartments in a single stage.

Types of Flocculators

Horizontal Shaft Flocculation

Vertical Turbine Flocculation

Hydraulic Flocculation



Sedimentation

A Process that utilize gravity to separate coagulated/flocculated particles from water

- Five operating parameters important to sedimentation.
- Identify the four zones of a sedimentation basin.
- Given the formula and required data, calculate each of the following: detention time, surface loading rate, mean flow velocity, and weir loading rate.
- Explain why tube or plate settlers increase settling efficiency.
- Identify five characteristics upon which the sedimentation process is dependent.

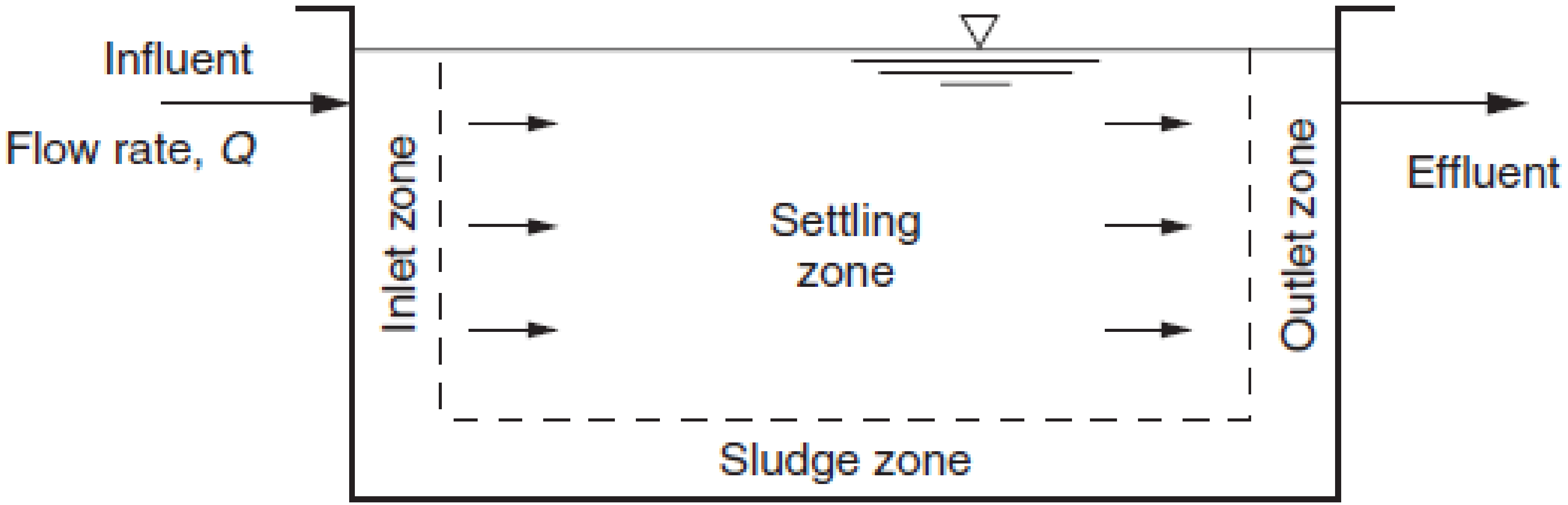
Basic Factors Affecting How Fast Particles Settle

1. Particle Size
2. Gravitational Settling Velocity
3. Particle Shape
4. Relationship of Downward Movement of Particle to Forward Flow Velocity
5. Water Temperature
6. Electrical Charge on Particles
7. Environmental Conditions

Sedimentation Basin (Sed. Basin)

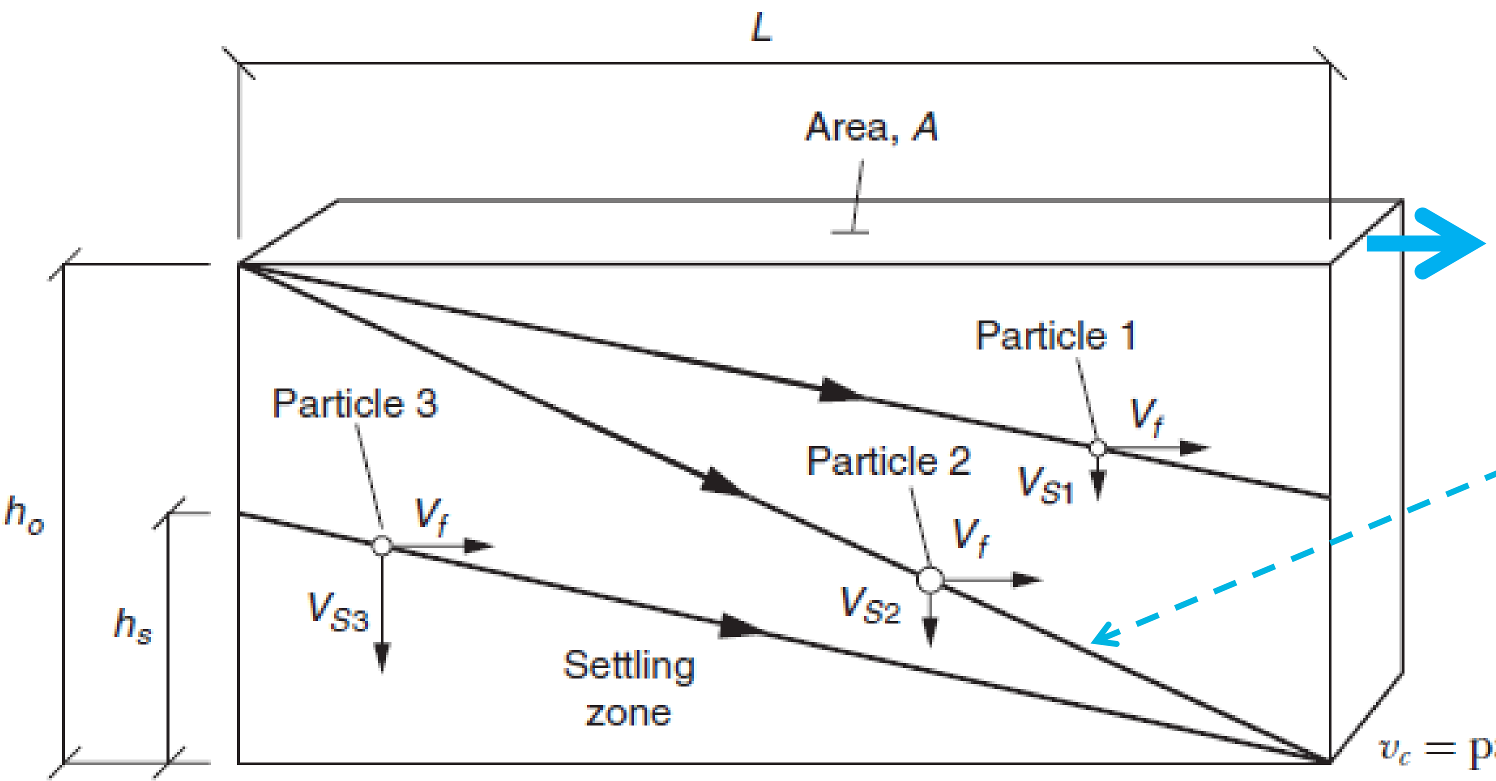
Zones Within a Sedimentation Basin (Sed Basin)

- Inlet Zone
- Settling Zone
- Sludge Zone
- Outlet Zone



Particle Settling

- Basic Assumption
  a. Plug Flow (no turbulence) & uniform horizontal velocity
  b. Particles are assumed to be removed if they reach the settling zone at the bottom



Critical Settling Velocity = Q/A

Depth of Sed Basin

$$v_c = \frac{h_o}{\tau}$$

Hydraulic Detention Time of a Sed Basin

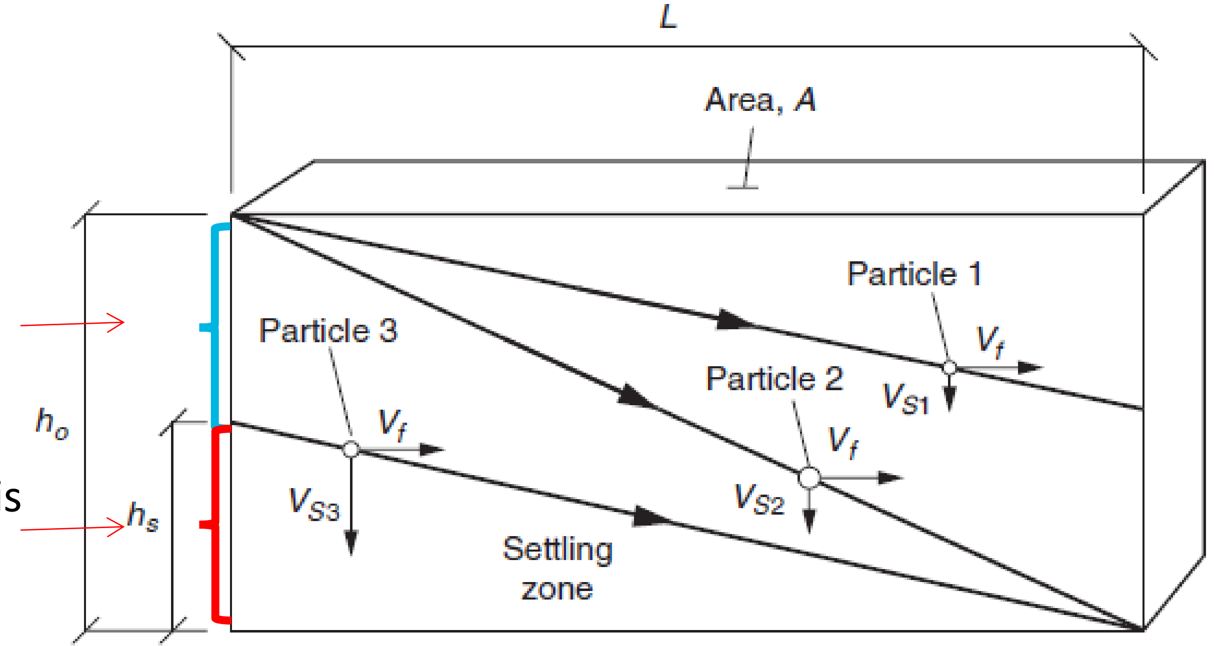
v_c = particle settling velocity such that particle at surface of inlet is removed in sludge zone just before outlet, m/h

For particles with a settling velocity < Vc…..

– Particles with a settling velocity Vc can also be removed; depending on their position in the inlet

Particles entering from this zone will not be removed

Particles entering from this zone will be removed



$$\text{Fraction of particles removed} = \frac{h_s}{h_o} = \frac{h_s/\tau}{h_o/\tau} = \frac{v_s}{v_c}\,(v_s < v_c) \qquad (10\text{-}18)$$

where h_s = height of particle from bottom of tank at position entering settling zone, m

v_s = particle settling velocity smaller than v_c, m/h

Example

Example 10-3 Particle removal in sedimentation basin

Calculate the particle removal efficiency in a rectangular sedimentation basin with a depth of 4.5 m, width of 6 m, length of 35 m, and process flow rate of 525 m^3/h. Compute the required sedimentation basin design parameters and plot the influent and effluent particle concentrations as a function of particle size using a histogram. Assume the following influent particle-settling characteristics (adapted from Tchobanoglous et al., 2003):

Settling Velocity, m/h	Number of Particles, #/mL
0–0.4	511
0.4–0.8	657
0.8–1.2	876
1.2–1.6	1168
1.6–2.0	1460
2.0–2.4	1314
2.4–2.8	657
2.8–3.2	438
3.2–3.6	292
3.6–4.0	292
Total	7665

Step 1

– Calculate Sed Basin's Overflow Rate (OR) & Critical Settling Velocity (Eq. 10-17)

$$OR = v_c = \frac{Q}{A} = \frac{525\ m^3/h}{(6\ m)(35\ m)} = 2.5\ m^3/m^2 \cdot h$$

Step 2

- Calculate Sed Basin's Overflow Rate (OR) & Critical Settling Velocity (Eq. 10-17)

$$OR = v_c = \frac{Q}{A} = \frac{525\ \text{m}^3/\text{h}}{(6\ \text{m})(35\ \text{m})} = 2.5\ \text{m}^3/\text{m}^2 \cdot \text{h}$$

- Calculate particle % removal for each size range (use average of the range)

Settling Velocity, m/h (1)	Average Settling Velocity, m/h (2)	Number of Influent Particles, #/mL (3)	Fraction of Particles Removed (4)
0–0.4	0.2	511	0.08
0.4–0.8	0.6	657	0.24
0.8–1.2	1.0	876	0.40
1.2–1.6	1.4	1168	0.56
1.6–2.0	1.8	1460	0.72
2.0–2.4	2.2	1314	0.88
2.4–2.8	2.6	657	1
2.8–3.2	3.0	438	1
3.2–3.6	3.4	292	1
3.6–4.0	3.8	292	1
Total		7665	

Fraction of particles removed

$$= \frac{h_s}{h_o} = \frac{h_s/\tau}{h_o/\tau} = \frac{v_s}{v_c}\ (v_s < v_c) \qquad (10\text{-}18)$$

where

h_s = height of particle from bottom of tank at position entering settling zone, m

v_s = particle settling velocity smaller than v_c, m/h

Step 3

- Calculate Number of particles removed for each size range

Settling Velocity, m/h (1)	Average Settling Velocity, m/h (2)	Number of Influent Particles, #/mL (3)	Fraction of Particles Removed (4)	Number of Particles Removed, #/mL (5)
0–0.4	0.2	511	0.08	41
0.4–0.8	0.6	657	0.24	158
0.8–1.2	1.0	876	0.40	350
1.2–1.6	1.4	1168	0.56	654
1.6–2.0	1.8	1460	0.72	1051
2.0–2.4	2.2	1314	0.88	1156
2.4–2.8	2.6	657	1	657
2.8–3.2	3.0	438	1	438
3.2–3.6	3.4	292	1	292
3.6–4.0	3.8	292	1	292
Total		7665		5090

Step 4

– Calculate number of particles remaining in the effluent

Settling Velocity, m/h (1)	Average Settling Velocity, m/h (2)	Number of Influent Particles, #/mL (3)	Fraction of Particles Removed (4)	Number of Particles Removed, #/mL (5)	Number of Particles in Effluent, #/mL (6)
✓	✓	✓	✓	✓	✓
0–0.4	0.2	511	0.08	41	470
0.4–0.8	0.6	657	0.24	158	499
0.8–1.2	1.0	876	0.40	350	526
1.2–1.6	1.4	1168	0.56	654	514
1.6–2.0	1.8	1460	0.72	1051	409
2.0–2.4	2.2	1314	0.88	1156	158
2.4–2.8	2.6	657	1	657	0
2.8–3.2	3.0	438	1	438	0
3.2–3.6	3.4	292	1	292	0
3.6–4.0	3.8	292	1	292	0
Total		7665		5090	2575

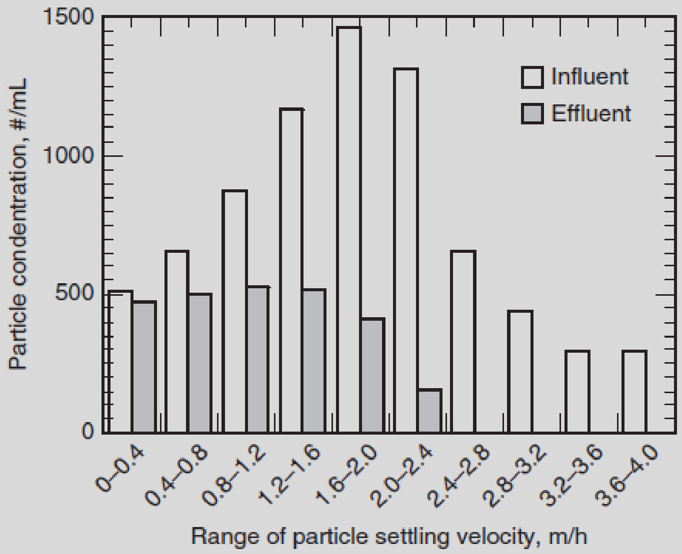
Step 5

– Compute the overall particle removal efficiency

$$\text{Removal efficiency} = \frac{5090}{7665} = 0.664 = 66.4\%$$

– Plot the influent & effluent particle concentrations for each settling velocity range

4. Plot the influent and effluent particle concentrations for each settling velocity range using a histogram.

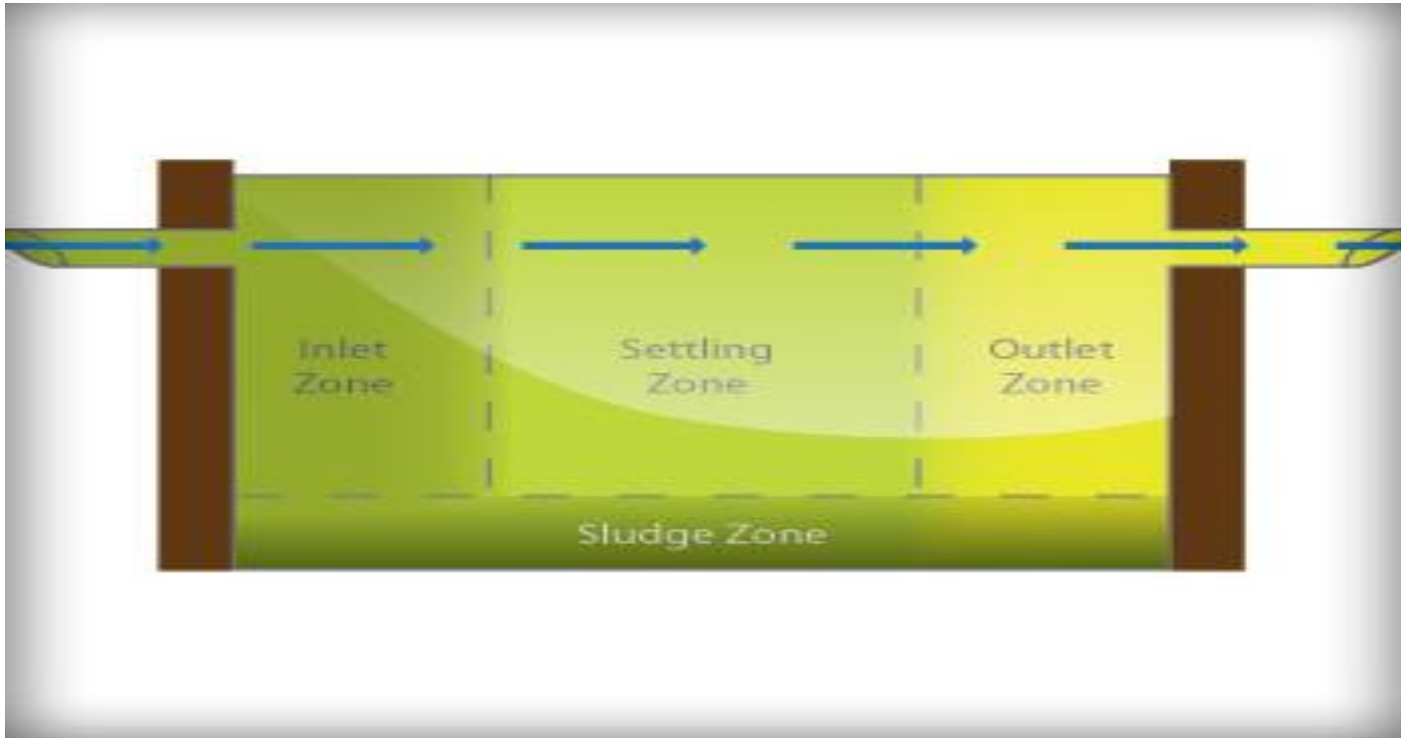


Differential Settling

- Particles aggregated at different sizes with different densities; thereby settling at different velocities
- Particles settle at different velocity will collides and form larger particles (and therefore flocculated)
- While theoretical particle settling rate can be calculated, actual settling rate in the field depends on water chemistry and temperature

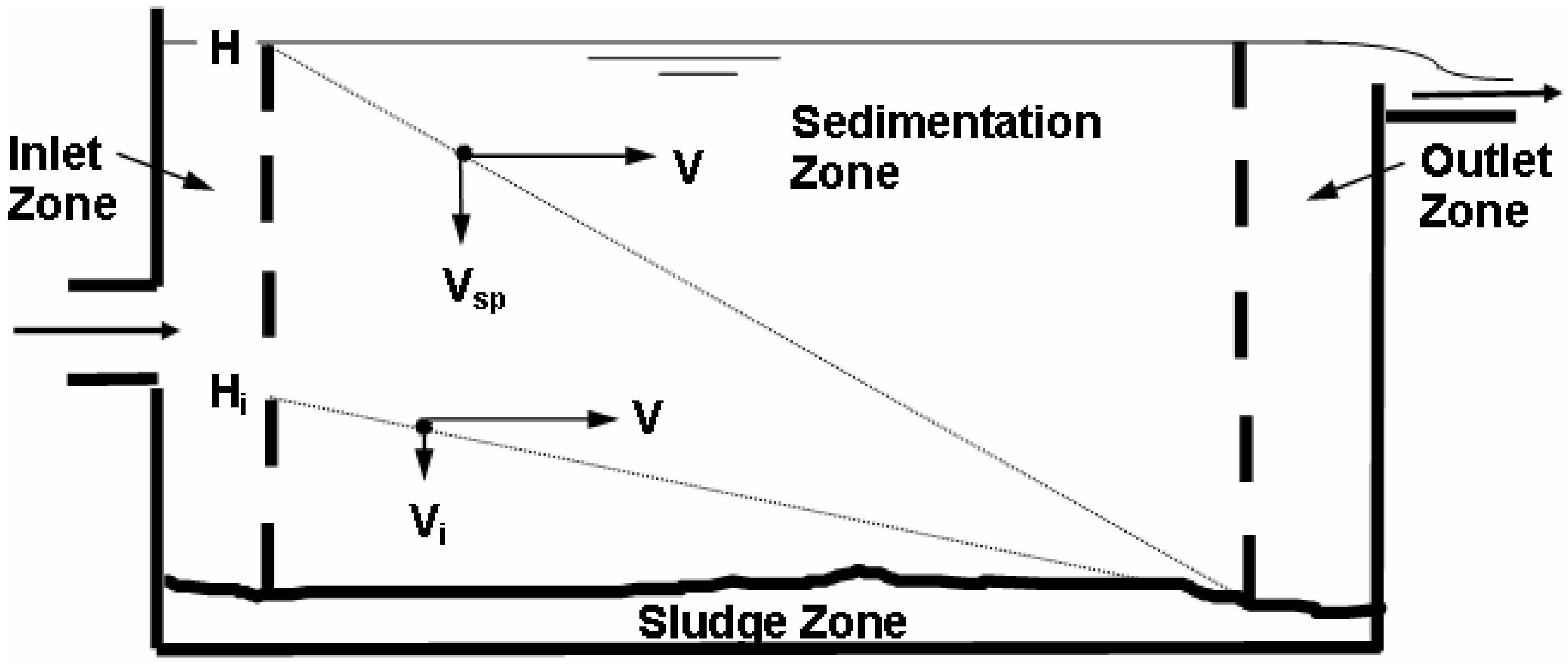
Potential Short Circuiting

– Short circuiting could happen when
  - Flowrate is much higher than design value (under designed)
  - Water temperature at the upper section is higher



Inlet Design for Sed Basin

– Multiple inlet points at various depth to avoid short circuiting and to increase particle removal



Note on Theoretical Design

- Theoretical design provides a solid foundation for modern water treatment
- Help to understand the reasons “behind the scene”
- Conventional treatment process performance can be affected by many factors
  - Raw water quality (pH, alkalinity, temperature, TOC level, etc.)
  - Type and quantity of chemicals used
  - Operational preferences
  - Level of raw water quality monitoring
  - Level of SOP for operation established and followed
- Level of operation knowledge, capability and level of sophistication varies from plant to plant

What are really used in the real world?

- Rely on experienced engineers' years of design experience (Maybe an AI opportunity?)
- Follow design standards established by each state based on decades of knowledge and field operation performance experience.
- 10 State Standards for Drinking Water System Design
- Each State may have its own standards or requirements
- You are strongly encouraged to consult with the 10 State Standards in your design project

http://10statesstandards.com/waterrev2012.pdf

Homework

– Reading Assignment: Chapter 9 & 10

Homework: Calculate solid generation from coagulation using ferric chloride

- Plant Capacity: 10 mgd
- Coagulant dose is 10 mg/L as $FeCl_3$
- Assume water content in the dewatered sludge is 75%

Q: How many lbs of dewatered solid will be generated daily?

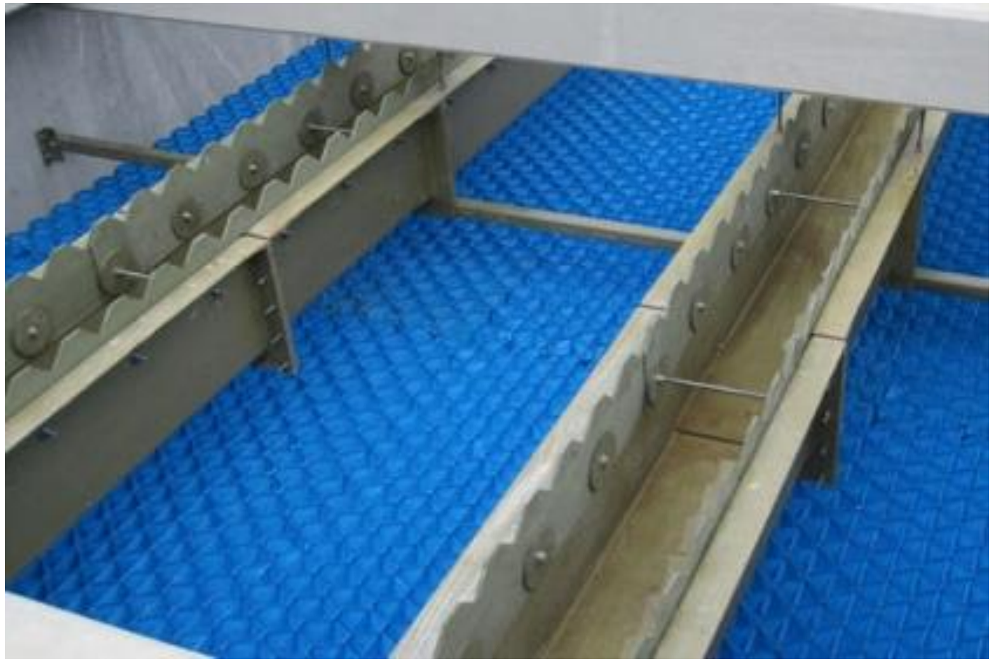
Hint: Mwt. for Fe is 55.85 and Mwt. For Cl is 35.45. When FeCl3 is hydrolyzed ferric hydroxides solid $Fe(OH)_3$ is formed.

High Rate Clarification Process

- Increasing surface loading rate from 3 – 4 gpm/ft^2 to > 12 gpm/ft^2
- High Rate Clarification is achieved via two main schemes
  - Reduce the distance that particles need to travel before they hit the “sludge zone”
  - Make particles heavier

Surface Loading Rate: Quantity of water can be treated per minute per ft^2 of surface area of a treatment process tank. A higher surface loading rate translates to a lower surface area needed of a treatment process, which translate to lower construction costs. However, it is also considered a more “aggressive operation scheme” in the eyes of regulators.

Tube Settler



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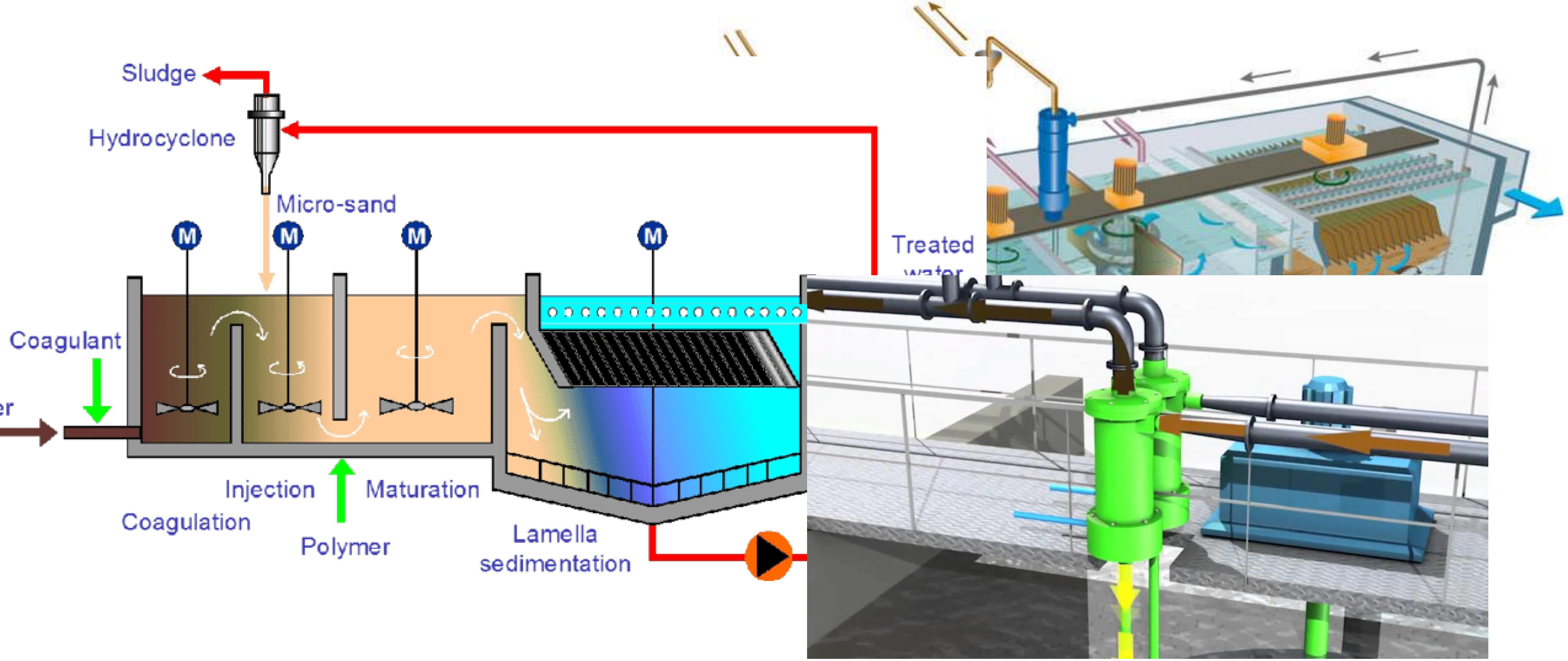
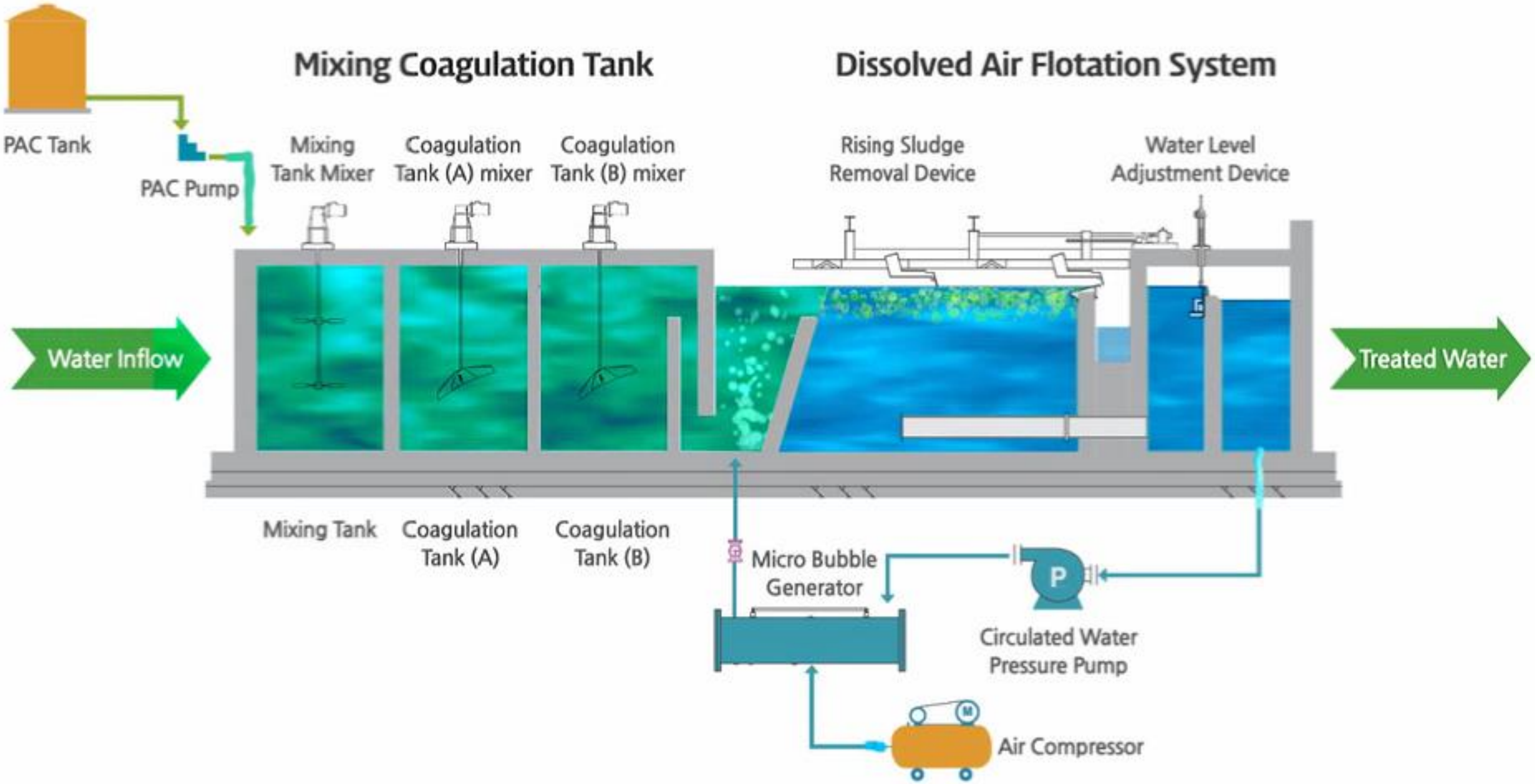
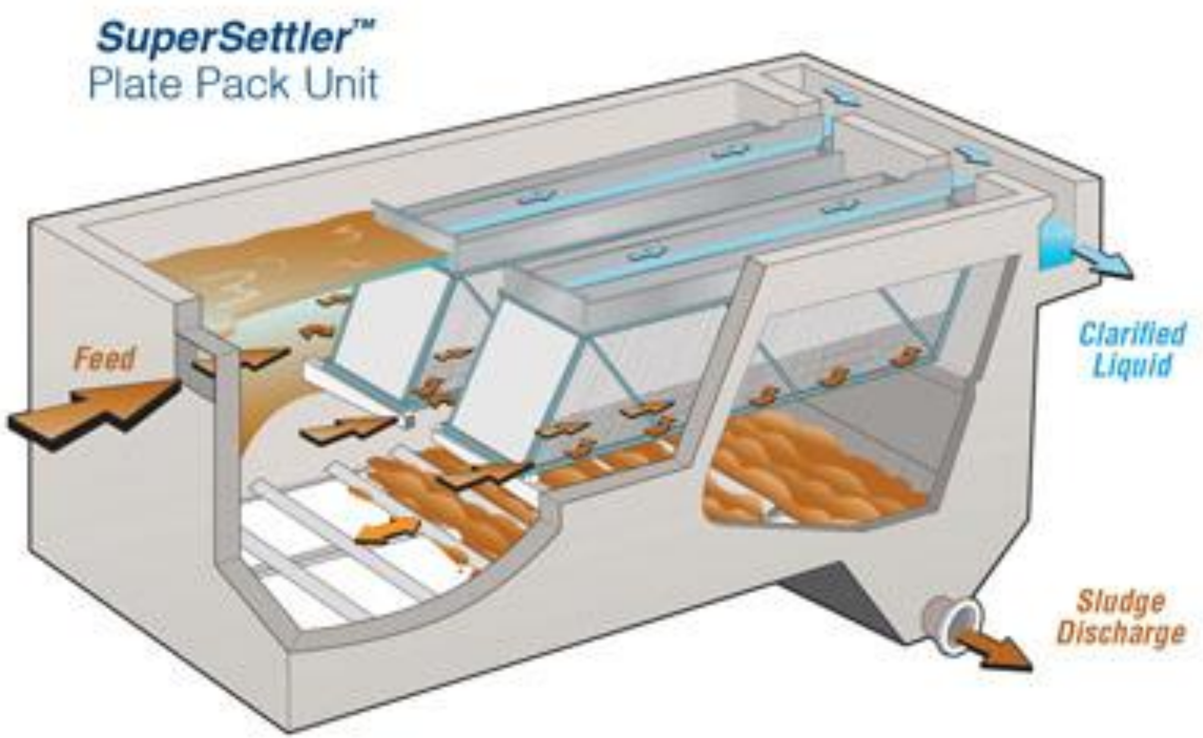

Sludge
Hydrocyclone
Micro-sand
M
M
M
M
Treated
Coagulant
Injection
Maturation
Coagulation
Polymer
Lamella
sedimentation

Loading rate

- Lamella Clarifier: 4 – 6 gpf/ft2
- DAF 4 – 6 gpf/ft2
- Actiflo: > 20 gpm/ft2


Mixing Coagulation Tank
Dissolved Air Flotation System
PAC Tank
PAC Pump
Mixing
Tank Mixer
Coagulation
Tank (A) mixer
Coagulation
Tank (B) mixer
Rising Sludge
Removal Device
Water Level
Adjustment Device
Water Inflow
Treated Water
Mixing Tank
Coagulation
Tank (A)
Coagulation
Tank (B)
Micro Bubble
Generator
P
Circulated Water
Pressure Pump
Air Compressor


SuperSettler™
Plate Pack Unit
Feed
Clarified
Liquid
Sludge
Discharge

Sludge Production

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