### Coagulation and Flocculation

**Water Treatment Course**

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#### Settling Velocities of Various Size Particles

<table>
<thead>
<tr>
<th>Particle size, mm</th>
<th>Type</th>
<th>Settling velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>Pebble</td>
<td>0.73 m/s</td>
</tr>
<tr>
<td>1</td>
<td>Course sand</td>
<td>0.23 m/s</td>
</tr>
<tr>
<td>0.1</td>
<td>Fine sand</td>
<td>0.6 m/min</td>
</tr>
<tr>
<td>0.01</td>
<td>Silt</td>
<td>8.3 m/day</td>
</tr>
<tr>
<td>0.0001</td>
<td>Large colloids</td>
<td>0.3 m/year</td>
</tr>
<tr>
<td>0.000001</td>
<td>Small colloids</td>
<td>3 m/million years</td>
</tr>
</tbody>
</table>
**COAGULATION**

- Coagulation is a chemical process in which charged particles (colloids) are destabilized.

  The addition and rapid mixing of coagulants
  
  The destabilization of colloidal and fine particles
  
  The initial aggregation of destabilized particles

**COLLOID STABILITY**

- **Colloids** - Particle size between 0.001 to 1.0 micron
- **Stable** - Colloidal suspensions that do not agglomerate naturally.
- Most colloids are stable \( \Rightarrow \) possess a negative charge
- Excessively large surface-to-volume ratio
- Surface phenomena predominate over mass phenomena
COLLOID STABILITY...

- Accumulation of electrical charges at the particle surface
- Can be hydrophilic- readily dispersed in water (organic colloids) or hydrophobic- no affinity for water; “stable in water because of electric charge (inorganic colloids)

When two colloids come in close proximity there are two forces acting on them.

- Electrostatic potential (Zeta potential) – a repelling force and,
- Van der Waals force – an attraction force.
COLLOID DESTABILIZATION

- A means of overcoming the energy barrier to create agglomeration of particles could be:
  - Brownian movement - random movement of smaller colloids may produce enough momentum to overcome the energy barrier and thus collide.
  - Mechanical agitation of the water - may impart enough momentum to larger particles to move them across the energy barrier.
  - These two processes are too slow and cannot be efficient means to remove particles.
  - Therefore, in order to destabilize the particles we must neutralize the charges on the particles.

COLLOID DESTABILIZATION...

- Neutralization can take place by addition of an ion of opposite charge to the colloid.
- Most colloids found in water are negatively charged → the addition of positively charged ions (Na\(^+\), Mg\(^{2+}\), Al\(^{3+}\), Fe\(^{3+}\) etc.) can neutralize the colloidal negative charges.
- Coagulant salts dissociate when added to water and produce positively charged hydroxo-metallic ion complexes (Me\(_q\)(OH)\(_p\)^{z+}\))
**Colloid Destabilization…**

- When complexes adsorb to the surface of the colloid, the zeta potential is reduced and particle is destabilized
- Destabilized particles aggregate by attraction due to van der Waals forces or chemical interactions between reactive groups available on the surface of the colloid

**Mechanisms of Destabilization**

- **Ionic layer compression.** A high ionic concentration compresses the layers composed predominantly of counter ions toward the surface of the colloid. Then the van der Waals force will be predominant so that the net force will be attractive and no energy layer will exist.

- **Adsorption and charge neutralization.** Surface charges are decreased when charged species (particularly trivalent) attach to the surface of the colloid.
**MECHANISMS OF DESTABILIZATION...**

- **Sweep coagulation.** The Al(OH)$_3$ forms in amorphous, gelatinous flocs that are heavier than water and settle by gravity. Colloids become entrapped or enmeshed by its “sticky” surface as the flocs settle.

- **Interparticle bridge.** Synthetic polymers linear or branched and are highly surface reactive. Thus, several colloids may become attached to one polymer and several of the polymer-colloid groups may become enmeshed, resulting in a settleable mass.

**IMPURITIES REMOVED BY COAGULATION**

- Miscellaneous fragments of animals and vegetables
- Plankton, mainly phtoplankton
- Colloids including clay
- Organic colouring matter
- A complex mixture of colloidal and dissolved organic compounds from wastewater
- Bacteria and viruses
FACTOR AFFECTING COAGULATION

- Types of coagulant
- Quantity or dose of coagulant
- Characteristics of water such as
  - Type and quantity of suspended matter
  - Temperature of water
  - pH of water
- Time, violence and method of mixing

COAGULANTS

- A coagulant is the substance (chemical) that is added to the water to accomplish coagulation.
- Three key properties of a coagulant:
  - Trivalent cation. most efficient cation
  - Nontoxic. For production of safe water
  - Insoluble in neutral pH range ➔ can precipitate without leaving high concentration of ions in water.
COAGULANTS...

- Commonly used coagulants are:
  - Alum: $\text{Al}_2(\text{SO}_4)_3 \cdot 14\text{H}_2\text{O}$
  - Ferric chloride: $\text{FeCl}_3$
  - Ferric sulfate: $\text{FeSO}_4$
  - Polyelectrolytes (Polymers)
- Aluminum salts are cheaper but iron salts are more effective over wider pH range

ALUMINUM

- either dry or liquid *alum*
- Alum have variable amount of water of crystallization $\rightarrow (\text{Al}_2(\text{SO}_4)_3 \cdot n\text{H}_2\text{O}$ ( n is 14 to 18)
- To produce the hydroxide floc, enough alkalinity should present in the water

$$\text{Al}_2(\text{SO}_4)_3 \cdot 14\text{H}_2\text{O} + 3\text{Ca(HCO}_3)_2 \rightarrow 2\text{Al(OH)}_3 \downarrow + 3\text{CaSO}_4 + 14\text{H}_2\text{O} + \text{CO}_2$$
- If alkalinity is not enough, then it should be added. Usually hydrated lime is used for that purpose

$$\text{Al}_2(\text{SO}_4)_3 \cdot 14\text{H}_2\text{O} + 3\text{Ca(OH)}_2 \rightarrow 2\text{Al(OH)}_3 \downarrow + 3\text{CaSO}_4 + 14\text{H}_2\text{O}$$
- Optimum pH is 5.5-6.5 and operating pH is 5 - 8
### Example: Alkalinity Calculation

- If 200 mg/L of alum to be added to achieve complete coagulation. How much alkalinity is consumed in mg/L as CaCO$_3$?
- Solution:
  - $594 \text{ mg} \quad 366 \text{ mg}$
  - $\text{Al}_2(\text{SO}_4)_3 \cdot 14\text{ H}_2\text{O} + 6\text{HCO}_3^- \Leftrightarrow 2\text{Al(OH)}_3\downarrow + 6\text{CO}_2 + 14\text{H}_2\text{O} + 3\text{SO}_4^{2-}$

- 594 mg alum consumes 366 mg HCO$_3^-$
- 200 mg alum will consume $\left(\frac{366}{594}\right) \times 200 \text{ mg HCO}_3^-$
  - $= 123 \text{ mg HCO}_3^-$

$$\text{Alkaline CaCO}_3 = 123 \times \frac{\text{Equivalent weight of CaCO}_3}{\text{Equivalent weight of HCO}_3^-}$$

- $= 123 \times \left(\frac{50}{61}\right)$
- $= 101 \text{ mg/L as CaCO}_3$

### Jar Test

- Is used to determine:
  - Proper coagulant
  - Proper coagulant aid
  - Proper coagulant dose
**Jar Test**

- **Procedure**
  - Add reagents (4 to 6 beakers)

- **Optimum pH:** 6.3
- **Optimum Coagulant Dose:** 12.5 mg/L

**pH Adjustment**

- Is used if pH of water to be treated is not within the optimum pH of the coagulant
- pH is increased using lime
- pH is reduced using sulfuric acid
**Alkalinity Addition**

- Is used when natural alkalinity is not enough to produce good floc
- Hydrated or slaked lime is used
- Soda ash (Na$_2$CO$_3$) is also used (expensive)

**Turbidity Addition**

- Is used to provide sufficient particulate concentration to achieve rapid coagulation through sufficient interparticle collision
- Is done by recycling chemically precipitated sludge
- Clays are also used for that purpose
**Coagulation-Flocculation Process Overview**

- The coagulation/flocculation process is a two-step process - the water first flows into the **Flash mix** (Rapid mix) chamber, and then enters the **flocculation basin**.

**Rapid Mixing and Flocculation**

- **Rapid mixing is used to:**
  - Disperse chemicals uniformly throughout the mixing basin
  - Allow adequate contact between the coagulant and particles
  - Microflocs are produced
  - Lasts only for about 45 secs

- **Flocculation is used to:**
  - Agglomerate microflocs to larger ones
### RAPID MIXING AND FLOCCULATION

- **Rapid mix** → Chemical mixing
- **Coagulation** → Destabilization
- **Floculation** → Floc formation
- **Sedimentation** → Flocs settle out

### RAPID MIXING

- Design parameters for rapid-mix units are mixing time $t$ and velocity gradient $G$.
- The **velocity gradient** is a measure of the relative velocity of two particles of fluid and the distance between.

\[
G = \sqrt{\frac{W}{\mu}} = \sqrt{\frac{P}{\mu V}}
\]

- $G =$ velocity gradient, sec\(^{-1}\)
- $W =$ power imparted per unit volume of basin, N-m/s-m\(^3\)
- $P =$ power imparted, N-m/s
- $V =$ basin volume, m\(^3\)
- $\mu =$ absolute viscosity of water (\(\mu=0.00131\) N-s/m\(^2\))
**Rapid Mixing Devices**

- A tank utilizing a vertical shaft mixer
- A pipe using an in-line blender
- A pipe using a static mixer.
- Hydraulic jump

**Rapid Mixing**

<table>
<thead>
<tr>
<th>Contact time t (s)</th>
<th>Velocity gradient, G (s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 – 1.0 (in-line blenders)</td>
<td>4,000</td>
</tr>
<tr>
<td>10-20</td>
<td>1,000</td>
</tr>
<tr>
<td>21-30</td>
<td>900</td>
</tr>
<tr>
<td>31-40</td>
<td>800</td>
</tr>
<tr>
<td>41-60</td>
<td>700</td>
</tr>
</tbody>
</table>
ROTARY MIXING

- Rotary mixing devices can be
  - Turbines
  - Paddle impellers
  - Propellers
- Basins are either circular or square in plan
- Depth of basin is 1 to 1.25 of the basin diameter or width
- Impeller diameter should be 0.3 to 0.5 of the tank width
- Baffled tanks are recommended since they minimize vortexing and rotational flow

EXAMPLE – RAPID MIXING

- A square rapid-mixing basin, with a depth of water equal to 1.25 times the width, is to be designed for a flow of 7570 m³/d. The velocity gradient is to be 790 s⁻¹, the detention time is 40 seconds, the operating temperature is 10° C, and the turbine shaft speed is 100 rpm. Determine:
  - The basin dimensions
  - The power required
  - \( \mu = 0.0013 \, \text{N-s/m}^2 \) at 10°C
**SOLUTION**

- Find the volume of the basin,
  \[ V = \frac{7570 \text{m}^3}{1440 \text{min}} \times \frac{\text{min}}{60 \text{sec}} \times 40 \text{sec} = 3.5 \text{m}^3 \]

- The dimensions are
  \((W)(W)(1.25W) = 3.50 \text{ m}^3\)
  \(W = 1.41 \text{ m}\)
  The depth of the basin, \(H = (1.25)(1.41 \text{ m}) = 1.76 \text{ m}\)
  **Use** \(W = 1.41 \text{ m}; H = 1.76\)
  Using the velocity gradient equation
  \[ P = \mu G^2 V = (0.0013N - s/m^2)(790/\text{sec})(1.41 \times 1.41 \times 1.76 \text{m}^3) \]
  \[ P = 2863N - m/s \]

**FLOCCULATION**

- *Flocculation* is stimulation by mechanical means to agglomerate destabilized particles into compact, fast settleable particles (or flocs).
- The objective is to bring the particles into contact so that they will collide, stick together, and grow to a size that will readily settle.
- The flocculation process relies on turbulence to promote collisions.
- Fragile flocs require low G values (<5/sec)
- High-strength flocs require high G values (≈10/sec)
**FLOCCULATION**

**Gt values for flocculation**

<table>
<thead>
<tr>
<th>Type</th>
<th>G (s(^{-1}))</th>
<th>Gt (unitless)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-turbidity, color removal coagulation</td>
<td>20-70</td>
<td>60,000 to 200,000</td>
</tr>
<tr>
<td>High-turbidity, solids removal coagulation</td>
<td>30-80</td>
<td>36,000 to 96,000</td>
</tr>
<tr>
<td>Softening, 10% solids</td>
<td>130-200</td>
<td>200,000 to 250,000</td>
</tr>
<tr>
<td>Softening, 39% solids</td>
<td>150-300</td>
<td>390,000 to 400,000</td>
</tr>
</tbody>
</table>

• Values of Gt from \(10^4\) to \(10^5\) are commonly used, with t ranging from 10 to 30 min.

**FLOCCULATION BASINS**

• Flocculation is normally accomplished with
  - an axial-flow impeller,
  - a paddle flocculator, or
  - a baffled chamber

• Flocculation basins are composed of minimum 3 compartments to:
  - Minimize short circuiting
  - Facilitate tapered flocculation

• For cross-flow, tapered flocculation can be provided by:
  - Varying the paddle size
  - Varying the number of paddles
  - Varying the diameter of the paddle wheels
  - Varying the rotational speed of the various shafts
FLOCCULATION TANK DESIGN DATA

Floculation Tank Design Data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Typical value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity gradient, G</td>
<td>20–80 s⁻¹</td>
</tr>
<tr>
<td>Detention time, t</td>
<td>20–30 min</td>
</tr>
<tr>
<td>Gt value</td>
<td>20,000–150,000</td>
</tr>
<tr>
<td>Configuration</td>
<td>Rectangular</td>
</tr>
<tr>
<td>Length to width ratio</td>
<td>4:1</td>
</tr>
<tr>
<td>Maximum stage volume</td>
<td>12,500 ft³ (304 m³)</td>
</tr>
<tr>
<td>Depth</td>
<td>12 ft (3.6 m)</td>
</tr>
<tr>
<td>Horizontal mixing</td>
<td>V between 1,860 and 10⁶ ft³ (53 and 28,000 m³)</td>
</tr>
<tr>
<td>Vertical mixing</td>
<td>V between 18,000 and 25,000 ft³ (509 and 707 m³)</td>
</tr>
<tr>
<td>Variable-speed motors</td>
<td>60% efficient</td>
</tr>
<tr>
<td>Freeboard and mixing apparatus</td>
<td>Require 20% of tank volume</td>
</tr>
<tr>
<td>Vertical mixers</td>
<td>Three-blade propeller impeller with ( R_s ) max of 10⁴</td>
</tr>
<tr>
<td>Horizontal paddle mixers</td>
<td>Eight (four arms with two paddles)</td>
</tr>
<tr>
<td>Total paddle-blade area</td>
<td>Less than 20% of tank cross-sectional area</td>
</tr>
<tr>
<td>Paddle tip velocity</td>
<td>Less than 2 ft/s (0.61 m/s) for weak floc, and 4 ft/s (1.22 m/s) for strong floc</td>
</tr>
</tbody>
</table>

EXAMPLE ON FLOCCULATION

A cross-flow, horizontal shaft, paddle wheel flocculation basin is to be designed for a flow of 25,000 m³/d, a mean velocity gradient of 26.7 sec⁻¹ (at 10° C), and a detention time of 45 minutes. The GT value should be from 50,000 to 100,000. Tapered flocculation is to be provided, and the three compartments of equal depth in series are to be used. The G values determined from laboratory tests for the three compartments are G₁ = 50/sec, G₂ = 20/sec, and G₃ = 10/sec. These give an average G value of 26.7/sec. The compartments are to be separated by slotted, redwood baffle fences, and the floor of the basin is level. The basin should be 15 m in width to adjoin the settling tank. Determine:

1. The GT value
2. The basin dimensions
3. The power to be imparted to the water in each compartment
**SOLUTION**

The GT value = \((26.7/\text{sec})(45 \text{ min})(60 \text{ sec/min})\) = 72,100

Since GT value is between 50,000 and 100,000, the detention time is satisfactory.

Basin volume, \(V = \text{(flow)} \times \text{(detention time)} = (25,000 \text{ m}^3/\text{d})(45 \text{ min})(\text{hr}/60 \text{ min}) = 781 \text{ m}^3\)

Profile area = \((\text{volume} / \text{width}) = (781 \text{ m}^3 / 15 \text{ m}) = 52.1 \text{ m}^2\)

Assume compartments are square in profile, and \(x\) is the compartment width and depth.

Thus, \((3x)(x) = 52.1 \text{ m}^2 = 17.37 \rightarrow x = 4.17 \text{ m and } 3x = 3(4.17) = 12.51 \text{ m}\)

Then, \(\text{width} = \text{depth} = 4.17 \text{ m and length} = 12.51 \text{ m}\)

\(\text{volume} = (4.17)(12.51)(15.0) = 783 \text{ m}^3\)

The Power, \(P = \mu G^2 V \quad \text{(at } 10^\circ \text{C, } \mu = 0.00131 \text{ N-s/m}^2)\)

\(P\) (for 1st compartment) = \((0.00131 \text{ N-s/m}^2)(50^2/2^2)(783 \text{ m}^3/3) = 855 \text{ N-m/s} = 855 \text{ J/s} = 855 \text{ W}\)

\(P\) (for 2nd compartment) = \((0.00131)(20^2)(783/3) = 137 \text{ W}\)

\(P\) (for 3rd compartment) = \((0.00131)(10^2)(783/3) = 34.2 \text{ W}\)

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**EXAMPLE**

A water treatment plant is being designed to process 50,000 m\(^3\)/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 \(\times\) 10\(^4\) produces optimal results at the expected water temperatures of 15\(^\circ\)C.

Determine:

- The monthly alum requirement.
- 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.
- The power requirement.
**SOLUTION**

- Monthly alum requirement:
  
  \[
  40 \text{ mg/L} = 0.04 \text{ kg/m}^3
  \]
  
  And
  
  \[
  \frac{0.04 \text{ kg}}{\text{m}^3} \times 50,000 \frac{\text{m}^3}{d} \times 30 \frac{d}{mo} = 60,000 \text{ kg/mo}
  \]

- Basin dimension:
  
  a. Assume an average G value of 30 s\(^{-1}\)

  \[
  Gt = 4.0 \times 10^4
  \]

  \[
  t = 4.0 \times 10^4 / (30 \times 60) \text{ min}
  \]

  \[
  t = 22.22 \text{ min}
  \]

  b. Volume of the tank is

  \[
  V = Q t = 50,000 \text{ m}^3/d \times 22.22 \text{ m/m} \times 1 \text{ d/1440 min}
  \]

  \[
  = 771.5 \text{ m}^3
  \]

**SOLUTION...**

- 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 are of each compartment should be square, i.e., depth equals 1/3 length. Assuming maximum depth of 5 m, length is

  \[
  3 \times 5 = 15 \text{ m}
  \]

  and width is

  \[
  5 \times 15 \times w = 771.5
  \]

  \[
  w = 10.3 \text{ m}
  \]
SOLUTION...

- Power requirements
  - Assume G value tapered as follows
    - First compartment, $G = 40 \text{ s}^{-1}$
    - Second compartment, $G = 30 \text{ s}^{-1}$
    - Third compartment, $G = 20 \text{ s}^{-1}$

The Power, $P = \mu G^2 V$ (at $15^\circ C$, $\mu = 0.001139 \text{ N-s/m}^2$)

- $P$ (for 1st compartment) = $(0.001139 \text{ N-s/m}^2)(40^2/\text{s}^2)(771.5 \text{ m}^3/3) = 470 \text{ W}$
- $P$ (for 2nd compartment) = $(0.001139)(30^2)(771.5/3) = 260 \text{ W}$
- $P$ (for 3rd compartment) = $(0.00139)(20^2)(771.5/3) = 120 \text{ W}$

Any Questions?