Lecture 5: Coagulation and Flocculation

Prepared by
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Colour in water
**Definitions**

**Coagulation** is a water treatment process that causes very small suspended particles to attract to one another and form larger particles.

consist of adding a floc-forming chemical reagent to a water to enmesh (catch) or combine with non-settleable colloidal solids and slow-settling suspended solids to produce a rapid-settling floc.

**Flocculation** is a water treatment process following coagulation, which uses gentle stirring to bring the suspended particles together so they will form larger more settleable clumps called floc.
Many of the contaminants in water contain matter in the colloidal form.

These colloids result in a stable “suspension”.

In general the suspension is stable enough so that gravity forces will not cause precipitation of these colloidal particles.

So they need special treatment to remove them from the aqueous phase. This destabilization of colloids is called “coagulation”.
## Settling time of particles with a density of 2,650 kg/m³

<table>
<thead>
<tr>
<th>Diameter (m)</th>
<th>Type of particles</th>
<th>Settling times over 30 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1.10^{-2}$</td>
<td>gravel</td>
<td>0.3 sec</td>
</tr>
<tr>
<td>$1.10^{-3}$</td>
<td>Coarse sand</td>
<td>3 sec</td>
</tr>
<tr>
<td>$1.10^{-4}$</td>
<td>Fine sand</td>
<td>38 sec</td>
</tr>
<tr>
<td>$1.10^{-5}$</td>
<td>silt</td>
<td>33 min</td>
</tr>
<tr>
<td>$1.10^{-6}$</td>
<td>bacteria</td>
<td>35 hours</td>
</tr>
<tr>
<td>$1.10^{-7}$</td>
<td>clay</td>
<td>230 days</td>
</tr>
<tr>
<td>$1.10^{-8}$</td>
<td>colloids</td>
<td>63 years</td>
</tr>
</tbody>
</table>
Principles

In surface water particles difference in sizes are present.

A common classification is:

- Molecules sizes smaller than 1 nm
- Colloids generally with dimensions between 1 nm and 1 µm
- Suspended matter having sizes larger than 1 µm.

**colloids:** commonly present in surface water are humic acids, proteins, colloidal clay, silica and viruses.

**suspended matter:** Bacteria, algae, silt, sand and organic debris.

Suspended matter - when it is larger than 5-10 µm can be removed quite easily by filtration or sedimentation and filtration.

The removal of colloids is possible by slow filtration in cases the water is not strongly polluted.
### Particulate size (meters)

<table>
<thead>
<tr>
<th>Electromag Waves</th>
<th>X-rays</th>
<th>UV</th>
<th>Visible</th>
<th>Near Infrared</th>
<th>Far Infrared</th>
<th>Microwaves</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecules</td>
<td>Colloids</td>
<td>Suspended Solids</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Viruses</td>
<td>Bacteria</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Humic Acids</td>
<td>Algae</td>
<td>Clay/Silt</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sand</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Methods for Size Analysis</td>
<td>Electron Microscope</td>
<td>Optical Microscope</td>
<td>Coulter Counter</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Potential Removal Systems</td>
<td>Reverse Osmosis</td>
<td>Ultra Filtration</td>
<td>Gravity Separation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Activated Carbon</td>
<td>Media Filtration</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
There are several possible origins of primary surface charge:

1. **Adsorption of potential determining ions.**

   - This involves preferential adsorption of a specific type of ion on the surface of the colloid.

   - Adsorption is usually van der Waals or hydrogen bonding.

   - For example, a surfactant التوتر السطحي on clay surface, humic acid on silica, OH\(^{-}\) on many minerals.

   - The charge that results is a function of concentration and type of ion in solution, pH, etc.)
2. **Lattice imperfections or isomorphic replacement.** This is very common in clay minerals. For example, the isomorphic replacement of $\text{Al}^{3+}$ for $\text{Si}^{4+}$ as shown below.

$$\begin{array}{c}
\begin{array}{c}
\text{Si} \\
\text{O} \\
\text{Si} \\
\text{O} \\
\text{Si} \\
\text{O}
\end{array}
\end{array}$$

(No net charge)

$$\begin{array}{c}
\begin{array}{c}
\text{Si} \\
\text{O} \\
\text{Al} \\
\text{O} \\
\text{Si} \\
\text{O}
\end{array}
\end{array}^{-1}$$

(Net charge $-1$)
3. **Ionogenic groups at surface.** (ionizable surface groups such as carboxyl, amino, hydroxyl, sulfonic, etc.) The charge here is usually dependent on pH.
Electrical Double Layer (EDL):

If we put a charged particle in a suspension with ions, then the primary charge will attract counter ions (opposite charged ions) by **electrostatic attraction**.

The primary charge cannot attract an equal amount of counter charge because a gradient of counterions is established that drives the counterions away from the surface.

The formation of the electrical double layer (EDL) then occurs via **attraction of oppositely charged counterions** by the primary surface charge and then a diffusion of the counterions away from the surface.

**The counterions are mobile, the primary charge is not.**
The EDL development is schematically shown here:
When colloids are subjected to an electrical field they will migrate generally toward the positive electrode of the field.

They move because the inner part of the colloid (with higher charge density than the overall colloid) will respond to the field and leave the outer diffuse layer behind.

The EDL actually shears at a plane and the potential (voltage) of the EDL at this shear plane is called the Zeta Potential, \(z\).

The zeta potential represents the net charge between the primary charge and the counter charge in the EDL located between the surface and the shear plane.

It’s with this charge that the colloid interacts with other colloids.
As a result of this EDL there is a net electrostatic repulsion/attraction developed between colloids.
The net resultant force is a result of:

1. attractive potential energy (mostly van der Waals forces), $V_a$. These forces are very strong at short separation distances

\[ V_a \propto \frac{1}{r^6} \]

2. repulsion potential energy (electrostatic forces), $V_R$. (by Coulomb’s law).

\[ V_R \propto \frac{1}{r^2} \]
Zeta Potential Model

The magnitude of these forces is measured by the zeta potential, which is:

\[ Z = \frac{4\pi q d}{D} \]

where:
- \( Z \) is the zeta potential,
- \( q \) is the charge per unit area,
- \( d \) is the thickness of the effective charge layer, and
- \( D \) is the dielectric constant of the liquid.

The greater the zeta potential, the greater are the repulsion forces between the colloids and, therefore, the more stable is the colloidal suspension.
The interactions are:

The reduction of the zeta potential to a degree where the attractive van der Waals forces and the agitation provided cause the particles to combine;

The aggregation of particles by interparticulate bridging between reactive groups on the colloids;

The enmeshment of particles in the precipitate floc that is formed.

Chemicals reduce colloidal surface charge and form precipitates that enhance the clustering process and sedimentation.

Colloids will not settle or filter until they agglomerate to a larger size.
Briefly: There are two major forces acting on colloids:

1) **electrostatic repulsion** (simply, negative colloids repel other negatively charged colloids)

2) intermolecular, or van der Waals, attraction.
Coagulants can be used to reduce the electrostatic repulsive forces.

The electrostatic repulsion reduced by the addition of countercharged ions $[\text{Al}^{3+}]$.
Chemical coagulation:

The process in which chemicals like Al or Fe salts added to the water to transform the impurities after reaction with the hydrolyzing salts into large flocs, which can be removed easily by sedimentation and filtration.

Lowering of the charge responsible - if high enough - for the net repulsive force will lead to a situation where collisions can occur resulting in agglomeration.
Coagulation is defined - in a stricter sense - as the destabilization of colloids.

In waters with higher ionic strengths the colloids are already present in a destabilized form.

Destabilization here has been caused by the mono- and divalent ions present in the water (electrostatic coagulation).

Coagulants are added here to improve the flocculation kinetics.
After coagulation the destabilized particles can collide, aggregate so flocs can be formed. This step is called flocculation.

**Flocculation:** The process of agglomeration of the destabilized particles to such a size that separation by sedimentation and filtration is possible.

In flocculation one can make a distinction between perikinetic and orthokinetic flocculation. Brownian motion is the driving force in the agglomeration of destabilized particles up to µm-level perikinetic flocculation).

Above ~ 1 µm the influence of Brownian motion on the collision rate of the particles can be neglected, then artificial mixing is necessary to get an efficient flocculation. That part of the flocculation process is called orthokinetic flocculation.
In water treatment two main types of coagulants are used i.e. aluminum and iron salts.

<table>
<thead>
<tr>
<th>Type of coagulant</th>
<th>formula</th>
<th>most common form</th>
<th>reaction with water</th>
</tr>
</thead>
<tbody>
<tr>
<td>aluminum sulfate</td>
<td>Al$_2$(SO$_4$)$_3$.14-18H$_2$O</td>
<td>lumps or powder</td>
<td>acidic</td>
</tr>
<tr>
<td>Sodium aluminate</td>
<td>NaAlO$_2$ or Na$_2$Al$_2$O$_4$</td>
<td>Powder</td>
<td>alkaline</td>
</tr>
<tr>
<td>Poly-aluminiumchloride</td>
<td>Al$_n$(OH)$<em>m$Cl$</em>{3n-m}$</td>
<td>Solution or powder</td>
<td>acidic</td>
</tr>
<tr>
<td>Ferric sulfate</td>
<td>Fe$_2$(SO$_4$)$_3$.9H$_2$O</td>
<td>Small crystals</td>
<td>acidic</td>
</tr>
<tr>
<td>Ferris chloride</td>
<td>FeCl$_3$.6H$_2$O</td>
<td>Lumps or solution</td>
<td>acidic</td>
</tr>
<tr>
<td>Ferrous sulfate</td>
<td>FeSO$_4$.7H$_2$O</td>
<td>Small crystals</td>
<td>acidic</td>
</tr>
</tbody>
</table>
Before application one must always prepare a solution of the coagulants. In that solution the coagulant is most effective.

if it is present in the trivalent state i.e. Fe$^{3+}$ or At$^{3+}$ resulting in a pH of < 1.5 of the solution.

When a solution of alum is added to the water to be treated the following reactions take place.

Hydrolysis reaction: \[\text{Al}^{3+} + 3\text{H}_2\text{O} \rightarrow \text{Al(OH)}_3\downarrow + 3\text{H}^+\]

If enough alkalinity is present the following reactions can occur:

If CO$_3^{2-}$ is present: \[\text{CO}_3^{2-} + \text{H}^+ \rightarrow \text{HCO}_3^- + \text{H}_2\text{O}\]

or with HCO$_3^-$: \[\text{HCO}_3^- + \text{H}^+ \rightarrow \text{CO}_2 + \text{H}_2\text{O}\] resulting in a lowering of pH
The compounds formed are positively charged and can interact with the impurities like colloids.

The solubility of Al(OH)$_3$, is very low. So precipitation occur in the form of flocs.

As H$^+$ - and OH$^-$ -ions are involved the pH of the water during coagulation is important for the charge of the hydrolysis products.

The chemical composition of the water is important too because divalent ions like SO$_4^{2-}$ and HPO$_4^{2-}$ can replace the OH$^-$ -ions in the complex and hence can influence the properties of the precipitate
If enough alkalinity is present the H\(^+\)-ions formed will be taken away and the precipitate \([\text{Al(H}_2\text{O)}_3(\text{OH})_3]\) or just \(\text{Al(OH)}_3\) will be formed.

At pH-values higher than 7.8 aluminates-ions \([\text{Al(H}_2\text{O)}_2(\text{OH})_4]\) or just \(\text{Al(OH)}_4^-\) are formed which are negatively charged and soluble in water.

In coagulation with an aluminum compound pH-values higher than 7.8 must be avoided for that reason.
For iron compounds the same type of hydrolysis reactions take place:

\[ \text{Fe}^{3+} + 3\text{H}_2\text{O} \rightarrow \text{Fe(OH)}_3 + 3\text{H}^+ \]

followed by the reaction of the H\(^+\) ions with the alkalinity.

Here there exist the hydrated ferric-ion \([\text{Fe(H}_2\text{O)}_6]^{3+}\) with the same hydrolysis equations as for \([\text{Al(H}_2\text{O)}_6]^{3+}\).

The formation of \([\text{Fe(H}_2\text{O)}_2(\text{OH})_4]^-\) or \(\text{Fe(OH)}_4^-\) occurs only at high pH-values not common in conventional treatment, so the upper pH-limit for coagulation with \(\text{Fe}^{3+}\) is much higher than for \(\text{Al}^{3+}\) i.e. 10 instead of 7.8 (\(\text{Al}^{3+}\)).

Iron compounds have less tendency to form polynuclear species compared with aluminium.
The efficiency of the coagulation process is dependent upon a number of parameters like:

- The water quality
- The type and concentration of colloids (part of water quality)
- The type and dose of coagulant
- The value of pH during coagulation
  
  optimal pH-range for Al: 6 - 7.8  
  Fe$^3+$: 4 - 10  
  Fe$^2+$: > 8.5
- Temperature
- Mixing conditions

In practice the coagulation process involves a rapid mixing, flocculation, sedimentation and filtration step. Some of these steps are sometimes combined in water treatment practice.
JAR TESTS

coagulant added

coagulant forms precipitate, trapping impurities

precipitate and trapped impurities settle to bottom

impurities
The selection of a coagulant requires the use of laboratory or pilot plant coagulation studies.

Usually laboratory studies using the jar test are adequate for selecting a coagulant for a water treatment plant.

A jar test is usually used to determine the proper coagulant and coagulant aid, if needed, and the chemical dosages required for the coagulation of a particular water.

Samples of the water are poured into a series of containers.

Various dosages of the coagulant and coagulant aid are added.

The contents are rapidly stirred to simulate rapid mixing.

Then the contents are gently stirred to simulate flocculation.

After a given time, the stirring is ceased and the floc formed is allowed to settle.
The most important aspects to note are:

- The time for floc formation,
- The floc size,
- Its settling characteristics,
- The percent turbidity and color removed, and
- The final pH of the coagulated and settled water.

- The chemical dosage determined from the procedure gives an estimate of the dosage required for the treatment plant.
The jar test simulate the coagulation/flocculation process in a batch mode. A series of batch tests are run in which pH, coagulant type and dosage and coagulant aid are varied to get the optimal dosage (lowest residual turbidity).

An economic analysis is performed to select these parameters.

Jar tests generally are performed using 6 one-liter samples of the water to be treated.

To these samples a range of coagulant (and possibly coagulant aid) dose is added (one sample is usually a blank).
Immediately after the coagulant is added the samples are "flash mixed" for approximately one minute.

The stirrer speed is then reduced to simulate a flocculation basin.

Flocculation mode is generally maintained for about 20 minutes.

At the end of the flocculation period the stirrers are turned off and the floc is allowed to settle for one-half hour.

After this settling period supernatant samples are drawn off from each sample and analyzed for turbidity and sometimes alkalinity and pH.
Jar Test
Typical results from a jar test series might look like:

Coagulant Dose vs. Residual Turbidity

- Residual Turbidity (NTU)
- Dose (mg/L)

Graph showing
- FeCl₃ and Al₂(SO₄)₃ as coagulants.
Results of jar-test experiment with varying coagulant dosing

Results of jar-test experiment of with varying pH
Coagulation and Flocculation Process Design

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

Where,
\[ G = \text{velocity gradient, s}^{-1} \]
\[ P = \text{power input, W} \]
\[ V = \text{volume of water in mixing tank, m}^3 \]
\[ \mu = \text{dynamic viscosity, Pa.s} \]

**Viscosity** is a measure of the resistance of a fluid which is being deformed by either shear stress or tensile stress. The SI physical unit of dynamic viscosity is the pascal-second (Pa·s), which is identical to \( \text{N} \cdot \text{m}^{-2} \cdot \text{s} \).

**Velocity gradient** With respect to material being sheared, velocity gradient is the change \( dv \) in relative velocity \( v \) between parallel planes with respect to the change \( dr \) in perpendicular distance \( r \) throughout the depth of the material. Velocity gradient has the same dimensions as rate of shear, which is reciprocal seconds.
Rapid Mix

Types of Rapid Mixing Systems:

Mechanical devices in a dedicated basin (Most common application)

In-Line blenders (Efficient, Effective at all flows)

Hydraulic methods (Simple, effective, non-mechanical. Energy may vary with flow)

Air Mixing (Simple, advantages if aeration is required. Not common. May cause scum and floatable debris)
Mechanical Flash Mixers: Propeller Type
Mechanical Flash Mixers: Turbine Type

- Motor, TEFC, class F insulation, 460 v, 3 ph, 60 hz, 1.15 service factor
- Drive base with access openings
- Optional support structure with walkway surface and handrail
- Gear reducer
- Rigid coupling
- Liquid level
- Impeller shaft
- Turbine
- Chemicals introduced as close as possible to this point
In-Line Blenders: Mechanical Type
In-Line Blenders: Static Type

Chemical Feeders and Mixers

Optional feeder input disk—Teflon or Kynar

Spool lined with Teflon or Kynar

Removable element assembly made from solid Kynar, coated metal, or special material—e.g., Carpenter 20

Flow
Rapid Mix Design Considerations

Most chemical reactions in coagulation occur in less than 0.1 seconds. It is therefore important that mixing be as instantaneous and complete as possible.

Since $G$ is a measure of the mixing intensity, selection of $G$ and $Gt$ where $t$ is the detention time of the fluid in the rapid mixer, are important parameters in determining the proper mixing for both rapid mix and flocculation reactor design.

**Coagulation occurs in two ways:**

1) By adsorption of soluble hydrolysis coagulant species on the colloid particles and destabilization by charge neutralization. These reactions occur in about 1 second.

2) Sweep floc coagulation where the coagulant exceeds its solubility limit and precipitates and traps the colloid particles. Sweep floc coagulation occurs in the range of 1 to 7 seconds.
Jar tests can be used to determine which coagulation mechanism is predominant:

Charge reversal is predominant if dose-turbidity curves are parabolic in nature and have a minimum point. For this case G values in the range of 3,000 to 5,000 s\(^{-1}\) and detention times of about 0.5 s are recommended (1500 < Gt < 2,500). In-line blenders can be used.

If the dose response curve does not show charge reversal (is relatively flat at higher doses), then the predominant mechanism is sweep floc coagulation. For this case G values in the range of 600 to 1,000 s\(^{-1}\) and detention times of about 1 to 10 s are recommended (600 < Gt < 10,000).

In the softening process, for dissolution of CaO to Ca(OH\(_2\)), mixtures, detention times of 5 to 10 minutes are usually required. G values are around 700 s\(^{-1}\) and in-line blenders are typically not used.
Rapid Mix Tank Design

Maximum Tank Volume = 8 m³ (due to mixing equipment and geometry constraints)

Mixing Equipment: Electric Motor, gear-type speed reducer, turbine of axial shaft impeller.

Usually the turbine impeller provides more turbulence and is preferred in rapid mix tanks.

The tanks are usually, baffled horizontally into two or three compartments in-order to provide sufficient residence time.

Tanks should also be vertically baffled to minimize vortexing.

Chemicals should be added below the impeller, point of most mixing.
Mixing impeller types used in water treatment
Rapid Mix Tank
Rapid Mix Tank Design – Power Requirements

For the design of Rapid mix and flocculation tanks, the power imparted to the liquid in a baffled tank by an impeller may be described by the following equation for fully turbulent flow:

\[ P = K_T (n)^3 (D_i)^5 \rho \]

- \( P \) = power, \( W \)
- \( K_T \) = impeller constant
- \( n \) = rotational speed, revolutions/s
- \( D_i \) = impeller diameter, \( m \)
- \( \rho \) = density of liquid, \( \text{kg/m}^3 \)

For un-baffled tanks, the power imparted may be as low as one-sixth of that predicted by this equation.
The impeller constant, $K_T$, can be obtained from the following table:

Values of the impeller constant, $K_T$

<table>
<thead>
<tr>
<th>Type of impeller</th>
<th>$K_T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propeller, pitch of 1, 3 blades</td>
<td>0.32</td>
</tr>
<tr>
<td>Propeller, pitch of 2, 3 blades</td>
<td>1.00</td>
</tr>
<tr>
<td>Turbine, 6 flat blades, vaned disc</td>
<td>6.30</td>
</tr>
<tr>
<td>Turbine, 6 curved blades</td>
<td>4.80</td>
</tr>
<tr>
<td>Fan turbine, 6 curved blades at 45°</td>
<td>1.65</td>
</tr>
<tr>
<td>Shrouded turbine, 6 curved blades</td>
<td>1.08</td>
</tr>
<tr>
<td>Shrouded turbine, with stator, no baffles</td>
<td>1.12</td>
</tr>
</tbody>
</table>
Common Rules of Thumb:

Design Liquid depth = 0.5 to 1.1 times the basin diameter or width.

Impeller diameter is between 0.3 and 0.50 times the tank diameter or width.

Vertical baffles extend into the tank about 10% of the tank diameter or width.

Impellers typically do not exceed 1.0 meter in diameter.

Liquid depth may be increased to between 1.1 and 1.6 times the tank diameter if dual impellers on the shaft are employed. When dual impellers are employed, they are spaced about two impeller diameters apart.

Transfer efficiency of motor power to water power is about 0.8 for a single impeller.
EXAMPLE OF RAPID MIX TANK DESIGN

A city is planning for the installation of a water treatment plant to remove iron. A low-turbidity iron coagulation plant has been proposed with the following design parameters:

\[ Q = 2 \text{ m}^3/\text{s} \]

Rapid mix detention time, \( t = 10 \text{ s} \)

Rapid mix \( G = 1,000 \text{ s}^{-1} \)

Design a rapid-mix basin and size the mixing equipment.
Solution:
The volume of the rapid-mix tank by is:

\[ V = Q \times t = (2 \text{ m}^3/\text{s})(10 \text{ s}) = 20\text{ m}^3 \]

Since the minimum tank volume is 8 m\(^3\) is a guideline, tanks in parallel will have to be provided.

The design is also constrained by the availability of mixers and those limitations need to be evaluated.
Assume the following mixers are available:

<table>
<thead>
<tr>
<th>Model</th>
<th>Rotational speeds, rpm</th>
<th>Power, kW</th>
<th>Model</th>
<th>Rotational speeds, rpm</th>
<th>Power, kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>JTQ25</td>
<td>30,45</td>
<td>0.18</td>
<td>JTQ300</td>
<td>110,175</td>
<td>2.24</td>
</tr>
<tr>
<td>JTQ50</td>
<td>30,45</td>
<td>0.37</td>
<td>JTQ500</td>
<td>110,175</td>
<td>3.74</td>
</tr>
<tr>
<td>JTQ75</td>
<td>45,70</td>
<td>0.56</td>
<td>JTQ750</td>
<td>110,175</td>
<td>5.59</td>
</tr>
<tr>
<td>JTQ100</td>
<td>45,110</td>
<td>0.75</td>
<td>JTQ1000</td>
<td>110,175</td>
<td>7.46</td>
</tr>
<tr>
<td>JTQ150</td>
<td>45,110</td>
<td>1.12</td>
<td>JTQ1500</td>
<td>110,175</td>
<td>11.19</td>
</tr>
<tr>
<td>JTQ200</td>
<td>70,110</td>
<td>1.5</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

rpm = revolutions per minute
JTQ models have variable speeds from 1-45 rpm
The largest available mixer can achieve a water power of:

\[
(11.19\text{ kW})(0.8) = 8.95\text{ kW}
\]

The 0.8 is the assumed efficiency of transfer of motor power to water power. Given a G of 1,000 s\(^{-1}\), and a viscosity at 18\(^\circ\)C as 1.053x10\(^{-3}\) Pa\cdot s, the required mixing can be calculated as:

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

\[
V = \frac{P}{G^2 \mu} = \frac{8.95 \times 10^3 \text{ W}}{(1,000 \text{ s}^{-1})^2 (1.053 \times 10^{-3} \text{ Pa} \cdot \text{s})} = 8.50 \text{ m}^3
\]
This means that using the largest available mixer from the manufacturer, to supply 20 m³ volume requirement the number of tanks needed are:

\[
\text{Number of Tanks} = \frac{\text{total tank volume required}}{\text{volume requirement per tank based on mixing}} = \frac{20\text{ m}^3}{8.50\text{ m}^3 / \text{tank}} = 2.35 \text{ or } 3 \text{ rapid mix tanks}
\]

The volume for each tank is 6.67 m³. For the JTQ1500 the rotational speed is 110 rpm (1.83 rps) and a turbine with six flat blades (vaned disc), the impeller diameter can be estimated as:

\[
P = K_T (n)^3 (D_i)^5 \rho
\]

\[
D_i = \left( \frac{P}{(K_T)(n)^3 (\rho)} \right)^{1/5} = \left( \frac{(8.95 \times 10^3 \text{ W})}{(6.30)(1.83\text{ rps})(1.053 \times 10^{-3} \text{ Pa} \cdot \text{s})} \right)^{1/5}
\]

\[
= (0.23)^{1/5} = 0.75 \text{ m}
\]
Using a ratio of impeller diameter to tank diameter of 0.33, the tank diameter would be equal to:

\[
\left\{ \text{Tank diameter} \right\} = \frac{\text{impeller diameter}}{\text{ratio of impeller diameter to tank diameter}} = \frac{0.75 \text{ m}}{0.33} = 2.27 \text{ m}
\]

The surface area of the tank would be equal to:

\[
\left\{ \text{Tank surface area} \right\} = \frac{\pi}{4} (2.27 \text{ m})^2 = 4.05 \text{ m}^2
\]

With three 6.67 m\(^3\) tanks, the depth of each tank would be:

\[
\left\{ \text{Tank depth} \right\} = \frac{\text{tank volume}}{\text{tank area}} = \frac{6.67 \text{ m}^3}{4.05 \text{ m}^2} = 1.65 \text{ m}
\]
Need to check the liquid-depth to tank ratio:

\[
\left\{ \frac{\text{liquid depth}}{\text{tank diameter}} \right\} = \frac{1.65 \text{ m}}{2.27 \text{ m}} = 0.73
\]

This is within the guideline of 0.5 to 1.1.
FLOCCULATION

Flocculation is the most important parameter impacting particle removal efficiency.

The primary objective of flocculation is to bring particles in contact with one another so they will collide, stick together, and grow to a size that will easily settle.

The right amount of mixing will enable flocculation to occur without settling the particles out in the floc basin or shearing the particles due to over mixing.

The mixing for flocculation must be controlled in a narrow range and must be able to vary G by a factor of two or three.

The following table illustrates the required mixing for different types of floc particles encountered in water treatment.
### Table 1. 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>
Types of Flocculation Tanks

Mechanical Flocculators
Flocculation Practice in Water Treatment

Hydraulic Flocculators

Horizontal Channel Hydraulic Flocculator (plan)

Vertical Channel Hydraulic Flocculator (profile)
The axial flow flocculators are typically used because they impart a nearly constant G in each compartment.

Flocculators are designed to have a minimum of three compartments to provide for tapered mixing.

The velocity gradient, G is tapered so that it is larger in the first compartment and less is the other compartments as the floc grows.

Table (1) provides average values of G for the flocculation basins.

Some common rules of thumb for axial flow impellers are that the diameter of the impeller is between 0.2 and 0.5 times the width of the chamber and that the maximum impeller diameter is about 3 m.
FLOCCULATION – POWER REQUIREMENTS

PADDLE FLOCCULATORS:
The following equation can be used to calculate the power requirements for a paddle mixer:

\[ P = \frac{C_D A \rho (v_p)^3}{2} \]

- \( P \) = power imparted, kW
- \( C_D \) = paddles drag coefficient
- \( \rho \) = density of fluid, kg/m³
- \( A \) = cross sectional area of paddles, m²
- \( v_p \) = relative velocity of paddles with respect to fluid, m/s
Rules of thumb:

Paddle tip speed = 0.1 to 1.0 m/s

Relative velocity of the paddles to the fluid = = 0.6 to 0.75 the paddles tip speed.

Drag coefficient vary with length to width ratio.

Total paddle-blade area on a horizontal shaft not to exceed 15 to 20 percent of the total basin cross sectional area to avoid excessive rotational flow.
PNEUMATIC MIXER:

\[ P = KQ_a \ln \left( \frac{h + 10.33}{10.33} \right) \]

\( P \) = power imparted, kW
\( Q_a \) = air flow rate at atmospheric pressure, m\(^3\)/min
\( K \) = constant = 1.689
\( h \) = air pressure at the point of discharge, m
HYDRAULIC MIXER:

The following expression can be used for a hydraulic mixer:

\[ P = Q \gamma h \]

\( P \) = power imparted, kW
\( Q \) = fluid flow rate, \( \text{m}^3/\text{s} \)
\( \gamma \) = specific weight of fluid, \( \text{kN/m}^3 \)
\( h \) = head loss through the mixer, m

The specific weight of water is equal to the product of the density and the acceleration due to gravity. Typically at normal temperatures the specific weight of water is taken to be 9.81 \( \text{kN/m}^3 \).
An upflow solids contact basin can be used to provide, mixing, flocculation and sedimentation/clarification all in one tank as shown below.
EXAMPLE OF FLOCCULATION TANK DESIGN

A city is planning for the installation of a water treatment plant to remove iron. A low-turbidity iron coagulation plant has been proposed with the following design parameters:

\[ Q = 2 \text{ m}^3/\text{s} \]
Flocculation \( t = 20 \text{ minutes} \)
Flocculation \( G = 30 \text{ s}^{-1} \)
\( T = 18^\circ \text{C} \)

Design a flocculation system and size the mixing equipment.
The volume of the flocculation basin is:

\[ V = (Q)(t) = (2 \text{ m}^3/\text{s})(20 \text{ min})(60 \text{ s/min}) = 2,400 \text{ m}^3 \]

Need to divide the basin into three compartments. Each compartment will have the following volume:

\[ \text{Compartments} = \frac{\text{total volume}}{3 \text{ compartments}} = \frac{2,400^3}{3} = 800 \text{ m}^3 \]

Since the average G is 30 s\(^{-1}\), we will want to taper the mixing intensity such that it is reduced by 50% from the first compartment to the last compartment.

The design G for each compartment will be 40 s\(^{-1}\), 30 s\(^{-1}\) and 20 s\(^{-1}\) to yield an average of 30 s\(^{-1}\).
Following the same approach for the rapid mix system, we calculate the average maximum volume that can be mixed.

\[
V = \frac{P}{G^2 \mu} = \frac{8.95 \times 10^3 \text{ W}}{(30 \text{ s}^{-1})^2 (1.053 \times 10^{-3} \text{ Pa} \cdot \text{s})} = 9,444 \text{ m}^3
\]

For this G value the mixer power will not be limiting. Using 800 m³ tank and dividing it into three 267 m³ compartments, the power required for the first compartment would be:

\[
P_1 = G_1^2 \mu V = (40 \text{ s}^{-1})^2 (1.053 \times 10^{-3} \text{ Pa} \cdot \text{s}) (267 \text{ m}^3) = 450 \text{ W} = 0.450 \text{ kW}
\]

With 80 percent efficiency, the motor power should be:

\[
P_1 (\text{motor}) = 0.450 \text{ kW} / 0.8 = 0.5625 \text{ kW}
\]

The variable speed motors of JTQ75 should be evaluated.
Assuming a typical water depth of a flocculator of 4 m, and a square tank arrangement, the dimensions of the tank compartment would be:

\[
\begin{align*}
\{\text{Top area}\} &= \frac{\text{volume}}{\text{depth}} = \frac{267 \text{ m}^3}{4 \text{ m}} = 66.75 \text{ m}^2 \\
\text{and} \\
\{\text{Sides}\} &= (66.75 \text{ m}^2)^{1/2} = 8.17 \text{ m}
\end{align*}
\]

Using a diameter-to-width ratio of 0.3, the impeller diameter would be:

\[
\{\text{Impeller diameter}\} = (8.17 \text{ m})(0.3) = 2.45 \text{ m}
\]
Using a three-blade propeller with a pitch of 2, the required rotational speed would be:

\[
n^3 = \frac{(P)}{(K_T)(D_i)^5(\rho)} = \frac{(570 \text{ W})(0.8)}{(1.00)(2.45 \text{ m})^5 (1,000 \text{ kg/m}^3)} \\
= (0.005166)^{1/3} = 0.173 \text{ rps} = 10.4 \text{ rpm}
\]

This is within the variable speed range of 1 to 45 rpm for the JTQ-F motor.