Separation Processes

ChE 4M3

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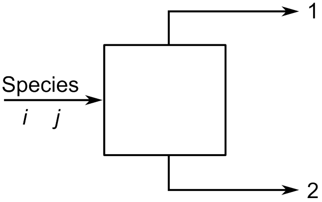
Last class: Separation factor

As mentioned, we will introduce a number of important principles we will re-use later.

Separation factor

$$S_{ij} = \frac{x_{i,1}/x_{j,1}}{x_{i,2}/x_{j,2}}$$



- select i and j so that $S_{ij} \geq 1$
- units of the x terms in the above equation can be mass or mole fractions (or flows)
- any units can be used, as long as you are consistent

Based on this definition: we can see why solid-fluid separations often have high separation factors

Mechanical separations

We will start with this topic

- It's easy to understand!
- Requires only a knowledge of basic physics (e.g. 1st year physics)
- It introduces a number of important principles we will re-use later
- Mechanical separations remain some of the most widely used steps in many flowsheets. Why?
  - reliable units
  - relatively inexpensive to maintain and operate
  - we can often achieve a very high *separation factor* (that's desirable!)

Units we will consider in depth

Under the title of "Mechanical Separations" we will consider:

- free settling (sedimentation)
- screening of particles
- centrifuges
- cyclones
- filtration

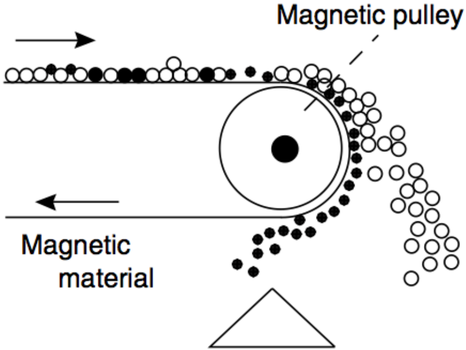
There are also others that go in this category. Deserving a quick mention are:

- magnetic separation
- electrostatic precipitation

Quick mention: Magnetic separation

- used mainly in the mineral processing industries
- high throughputs: up to 3000 kg/hour per meter of rotating drum
- e.g. remove iron from feed
- Also used in food and drug industries at multiple stages to ensure product integrity

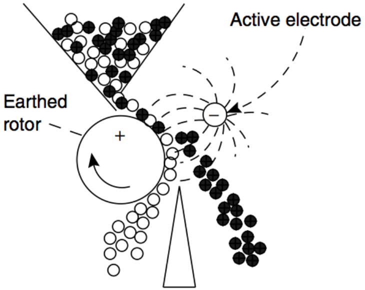
[Sinnott, 4ed, v6, Ch10]



Quick mention: Electrostatic separators

- depends on differences in conductivity of the material
- materials passes through a high-voltage field while on a rotating drum
- the drum is earthed
- some of the particles acquire a charge and adhere stronger to the drum surface
- they are carried further than the other particles, creating a split

[Sinnott, 4ed, v6, Ch10]



What is sedimentation?

Sugar video, http://www.youtube.com/watch?v=ZBOou6cahtw at `04:35 to 05:02`

DIY:

- concrete powder in water
- drywall compound (calcium carbonate and other particles) in water
- add vinegar to milk to make it curdle, stir, then settle

Definitions

Sedimentation

*Removal of suspended solid particles from a fluid (***liquid** *or gas) stream by gravitational settling.*

Most common to use a **liquid** rather than gas phase.

Some semantics:

- Thickening: generally aims to increase the solids to higher concentration; higher throughput processes
- Clarification: remove solids from a relatively dilute stream, usually aims for complete suspended-solids removal: units are deeper, and have provision for coagulation of feed.

Perry, 8ed, Ch 18.5

Where is it applied?

Most commonly:

- water treatment
- and mineral processing applications

But also chemical, pharmaceutical, nuclear, petrochemical processes use gravity settling to resolve emulsions or other liquid-liquid dispersions. [Svarovsky]

Topics we will cover

- factors that influence sedimentation
- designing a settler unit
- costs of building and operating a settler unit
- flocculation (coagulation)

List any factors that influence sedimentation process

- diameter of the particles
- i.e mass of particle (as long as density is constant)
- strength of gravitational field
- relative density of particle vs fluid
- density of fluid
- viscosity of fluid
- particle concentration (hindered)
- no effect: **diameter of the vessel** (or area)... to a point

Ideal case: momentum balance on an unhindered particle

Forces acting on a spherical particle in a fluid:

Assuming the fluid is stagnant.

Ideal case: momentum balance on an unhindered particle

Forces acting on a spherical particle in a fluid:

1. **Gravity**: a constant downward force $= mg = V_p \rho_p g$
2. **Buoyancy**: proportional to volume fluid displaced $= V_p \rho_f g$
3. **Drag**: opposes the particle's motion (next slide)
4. **Particle-particle interactions** and Brownian motion: assumed zero for now

$$
\begin{aligned}
V_p &= \text{particle's volume} = \frac{\pi D_p^3}{6} && [\mathrm{m}^3] \\
\rho_p &= \text{particle density} && [\mathrm{kg.m}^{-3}] \\
\rho_f &= \text{density of fluid} && [\mathrm{kg.m}^{-3}] \\
\mu_f &= \text{fluid's viscosity} && [\mathrm{Pa.s}] \\
g &= \text{gravitational constant} = 9.81 && [\mathrm{m.s}^{-2}] \\
D_p &= \text{particle's diameter} && [\mathrm{m}]
\end{aligned}
$$

Drag force

$$F_{\text{drag}} = C_D A_p \frac{\rho_f v^2}{2}$$

where

$$\begin{array}{rcll} v & = & \text{relative velocity between the particle and the fluid} & [\text{m.s}^{-1}] \\ A_p & = & \text{projected area of particle in direction of travel} & [\text{m}^2] \\ C_D & = & \text{drag coefficient (it's assumed constant!)} & [-] \\ \rho_f & = & \text{density of fluid (not the particle)} & [\text{kg.m}^{-3}] \end{array}$$

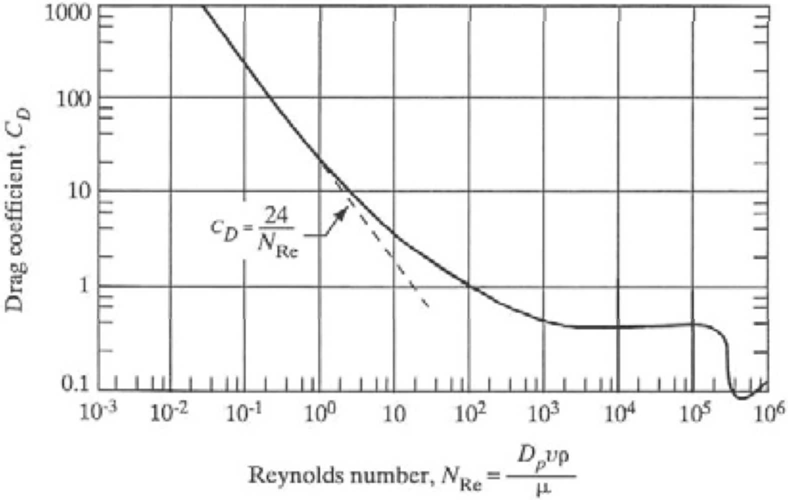
Estimating the drag coefficient, C_D

It's a function of Reynolds number $= \text{Re} = \dfrac{D_p v \rho_f}{\mu_f}$

[Richardson and Barker, p 150-153]

1. If $\text{Re} < 1$
$$C_D = \frac{24}{\text{Re}}$$
2. If $1 < \text{Re} < 1000$
$$C_D = \frac{24}{\text{Re}}\left(1 + 0.15\text{Re}^{0.687}\right)$$
3. If $1000 < \text{Re} < 2 \times 10^5$
$$C_D = 0.44$$
4. If $\text{Re} > 2 \times 10^5$
$$C_D = 0.10$$

Drag coefficient as a function of Re



Geankoplis, 3rd p818, 4th p921

Momentum balance (Newton's second law)

$$
\begin{aligned}
m\frac{dv}{dt} &= F_{\text{gravity}} - F_{\text{buoyancy}} - F_{\text{drag}} = 0 \qquad \text{at steady state} \\
0 &= V_p \rho_p g - V_p \rho_f g - C_D A_p \frac{\rho_f v^2}{2}
\end{aligned}
$$

Substitute $V_p = \dfrac{\pi D_p^3}{6}$ and $A_p = \dfrac{\pi D_p^2}{4}$ for spherical particles (A_p is the 2-D cross-sectional area) and solve for v:

Terminal velocity of an unhindered particle

$$
v = \sqrt{\frac{4\left(\rho_p - \rho_f\right) g D_p}{3 C_D \rho_f}} \qquad \text{(TSV)}
$$

Stokes' law

Simplification of the above equation when $\mathrm{Re} < 1$:

$$v = \frac{(\rho_p - \rho_f)\, g D_p^2}{18\mu_f}$$

Confirm it for yourself: *hint*: use the solution for a quadratic equation $ax^2 + bx + c = 0$

Solving the general equation for v

$v = fn(C_D)$, but $C_D = fn(\mathrm{Re}) = fn(v)$

1. Assume $\mathrm{Re} < 1$ (Stokes' region)
2. Solve for v using equation on slide **??**
3. Calculate Reynolds number, $\mathrm{Re} = \dfrac{D_p v \rho_f}{\mu_f}$
4. Was Reynolds number region assumption true? If so: stop.
5. If not, use new Re and recalculate C_D (see slide **??**)
6. Repeat from step 2 to 5 until convergence

Example: A particle 1mm in diameter, with density of 5000 $\dfrac{\mathrm{kg}}{\mathrm{m}^3}$ is settling in an unhindered environment of water. Calculate an estimate of its terminal velocity. [*ans*: 27 cm/second]

Why is the terminal velocity so important?

Design criterion

Terminal velocity of the *slowest particle* is our limiting design criterion

We will describe particle sizes soon. But for now, it is apparent that the feed material will have small and large particles.

We are designing the unit for the smaller particles.

Introducing “hindered settling”

http://www.youtube.com/watch?v=E9rHSLUr3PU

Most important points:

- large particles settle faster in low concentration (free settling)
- settling interface forms (independent of particle size)
- Stokes law (free settling) doesn’t apply
- interface’s height *vs* time plots are formed

Hindered settling

Particles will not settle as perfect spheres at their terminal velocity under a variety of conditions:

- if they are hindered by other particles
- they are non-spherical
- concentrated feeds: particles form clusters that tend to settle faster
- concentrated feeds: modify the apparent density and viscosity of the fluid
- upward velocity of displaced fluids
- small particles are dragged in the wake of larger particles
- ionized conditions can cause particle coagulation $\rightarrow$ larger diameters $\rightarrow$ faster settling

Video: http://www.youtube.com/watch?v=h8n3Nt4tPXU shows some of these issues

Hindered settling

For a high concentration of particles we have hindered settling. Stokes law doesn't apply in these cases.

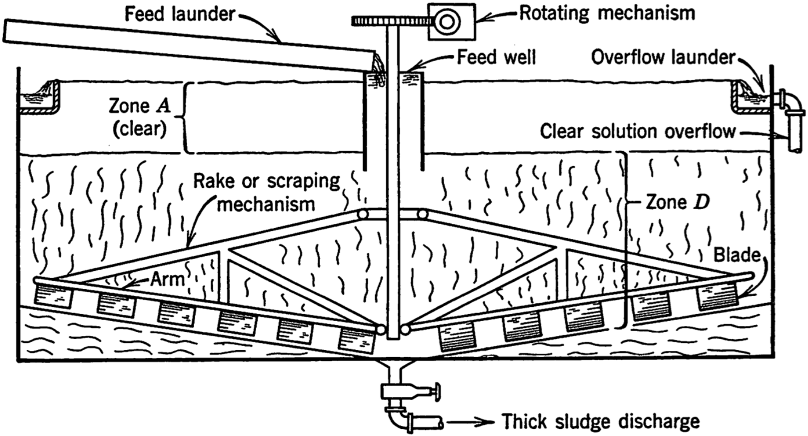
How to deal with this:

1. Modify the density, viscosity and other terms in the momentum balance (slide **??**): use correction factors
2. Resort to lab tests on samples that closely match the actual feed material
   - use lab results to design the settler

Let's see what these large-scale units look like.

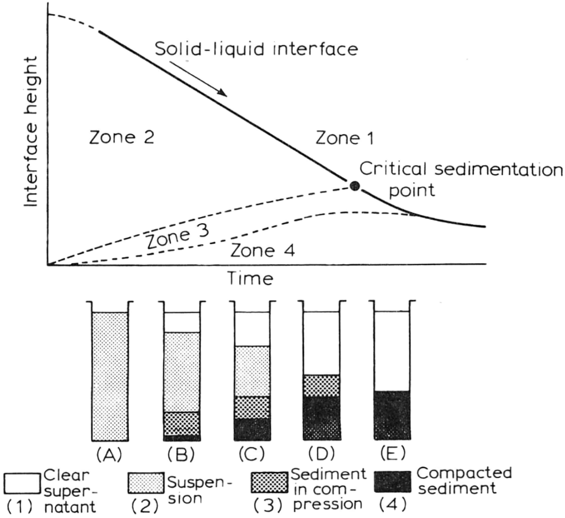
Large scale settlers

This unit operates on a continuous basis (at/close to steady-state)



Settling zones during sedimentation

We can run a batch experiment and observe settling rates



[Svarovsky, 3rd ed, p 135]

Settling zones during sedimentation

- initial constant rate of settling is observed
- a critical point is reached: point of inflection
- slow compression of the solids after this point

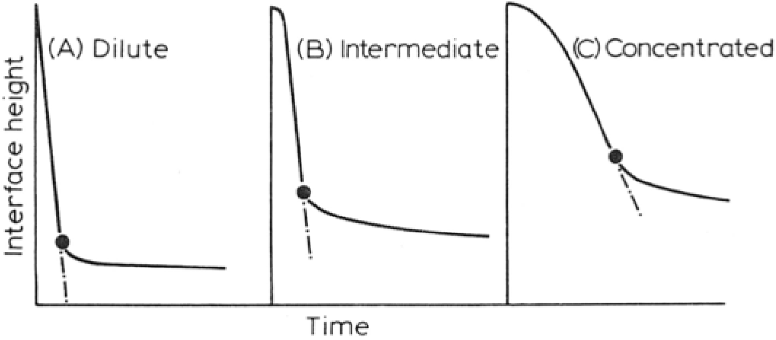
At least 2 procedures in the literature to design settlers from settling curves:

- Talmage and Fitch: tends to overdesign the area
- Coe and Clevenger: underdesign of the thickener area

[Svarovsky, 4ed, p 180]

In practice: we will rely on outside consultants and civil engineers, most likely, to size and design the unit. Else see the references at end for more details.

The effect of particle concentration



More concentrated solutions take longer to settle; sometimes see clearer supernatants with concentrated solutions: small particles are pulled down in wake of larger particles.

How can we accelerate settling?

- modify the particle shape: spherical vs needle shape (usually not possible)
- modify the fluid viscosity and density
  - not practical in most cases
  - e.g. used to separate diamonds in a process called "dense medium separation"
- raking or stirring: creates free channels for particles to settle in
- flocculation: to increase the particle's size by coagulating particles

Flocculation

MIT video on water cleaning:
http://www.youtube.com/watch?v=5uuQ77vAV_U

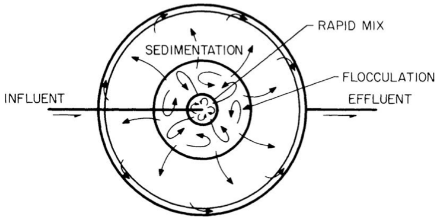
Please take notes from the video

Flocculation

Small particles (around $< 40\mu m$) and some biologically active particles will take unreasonably long times to settle, if at all. Flocculated particles cluster together and settle at higher rates

- impossible to predict shape and hence settling rate
- used in clarifiers, where clear supernatant is desired

Flocculation can be "included" with the sedimentation step:

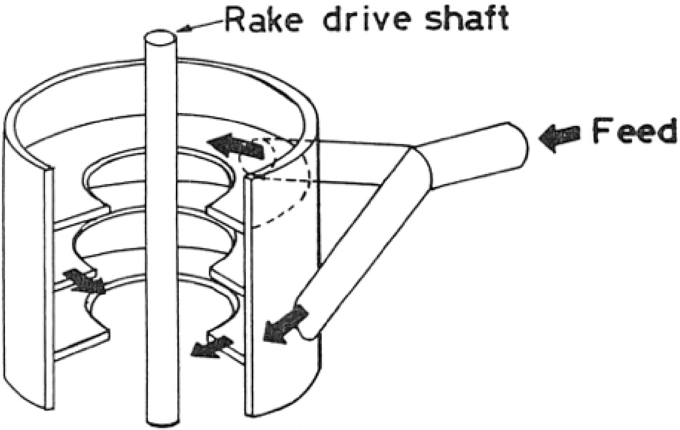


[Perry, 8ed, Ch22]

- important to not disrupt the flocs after contacting with flocculant: 30 seconds to 2 minutes contact time

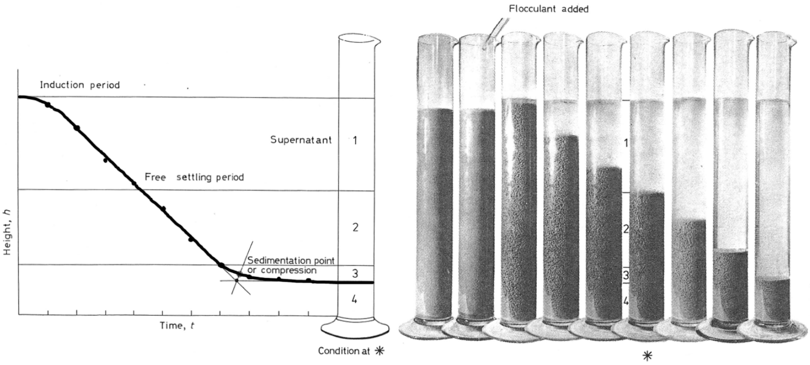
Feed area: feedwell

- aim to minimize turbulence from entry velocity
- avoid disruption to existing settling
- avoid breaking up existing flocs
- must not get clogged



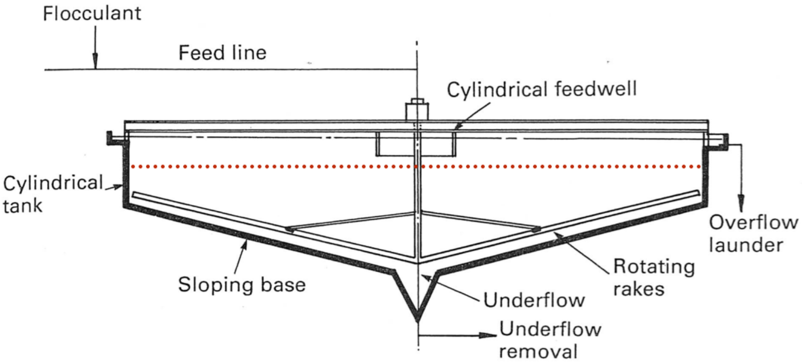
Sludge interface experiments

Since flocculant and concentration effects cannot be derived from theory, resort to lab settling tests.



Further settler terminology

A standard gravitational thickener:



[Svarovsky, 3ed, p141]

Unhindered settling: design principle

- Takes place when settling occurs at a constant rate, independent of other particles.
- Use the equations derived in last class to estimate settling velocity $= v$.
- Draw an imaginary horizontal layer through the settler and observe the mass of solids passing across it per unit time, per unit area = mass flux.
- The flux of solids is $\psi = C_0 v$, with units of $\dfrac{\text{kg solids}}{\text{m}^3 \text{ feed}} \cdot \dfrac{\text{meters}}{\text{second}}$
- $\psi = C_0 v \quad \dfrac{\text{kg solids}}{\text{second}} \cdot \dfrac{1}{\text{meters}^2}$
- $\psi =$ mass feed rate per unit area = loading rate = flux
- $\dfrac{1}{\psi} =$ unit area required per given amount of mass feed rate

Note: assuming no solids leave the overflow

Preliminary settler area estimate

The area required under these ideal conditions:

$$A = \frac{QC_0}{\psi} = \frac{QC_0}{C_0 v} = \frac{Q}{v}$$

where

$$Q = \text{volumetric feed rate} \quad \left[\frac{\text{m}^3 \text{ feed}}{\text{s}}\right]$$

$$C_0 = \text{concentration of solids in feed} \quad \left[\frac{\text{kg solids}}{\text{m}^3 \text{ feed}}\right]$$

$$v = \text{settling velocity} \quad \left[\text{m.s}^{-1}\right]$$

$$\psi = \text{mass feed rate per unit area} \quad \left[\frac{\text{kg solids}}{\text{s}} \cdot \frac{1}{\text{m}^2 \text{ area}}\right]$$

Example

A sample of material was settled in a graduated lab cylinder 300mm tall. The interface dropped from 500mL to 215mL on the graduations during a 4 minute period.

1. Give a preliminary estimate of the clarifier diameter required to treat a waste stream of 2100 L per minute. Over-design by a factor of 2, based on the settling rate, and account for about 7 m^2 of entry area used to eliminate turbulence in the entering stream.
2. If the feed concentration is 1.2 kg per m^3 feed, what is the loading rate? Is it within the typical thickener range of 50 to 120 kg per day per square meter? [Perry, 8ed, p22-79]

Answers:

1. Settling rate = 171 mm per 4 minutes = 42.8 mm/min.

   $$\text{Area} = \frac{2.1 \text{ m}^3.\text{min}^{-1}}{\left(\frac{1}{2}\right)\left(42.8 \times 10^{-3}\text{m.min}^{-1}\right)} = 98 + 7\text{m}^2$$

2. $$\psi = C_0 v = 1.2\frac{\text{kg}}{\text{m}^3} \cdot 0.0428\frac{\text{m}}{\text{min}} \cdot \frac{60 \times 24\text{min}}{\text{day}} = 74\frac{\text{kg}}{\text{day.m}^2}$$

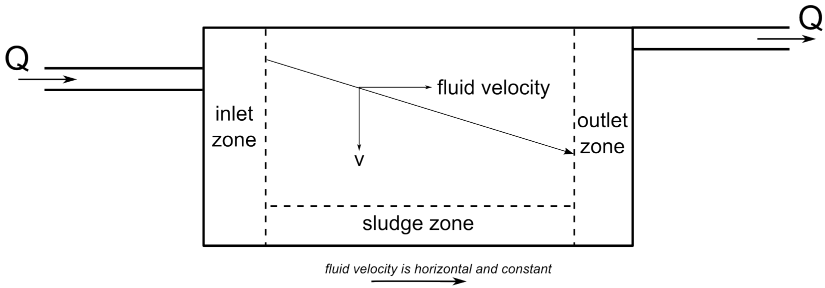
Settler design: shape, length, width

1. What width and depth should the settler be?
2. How long should the particles be in the settler? Does residence time matter?

Perry's, section 22.5.6:

- sedimentation tank can be rectangular or circular
  - rectangular: effluent weirs at the end
  - circular: around the periphery
- main concern: uniform flow in the tank (no short-circuits)
- removal efficiency = f(hydraulic flow pattern in tank)
  - incoming flow must be dissipated before solids can settle
  - evenly distributed; minimal disruption to existing fluid
  - overflow and underflow draw collected without creating hydraulic currents
  - solids are removed by scraping, and hydraulic flow

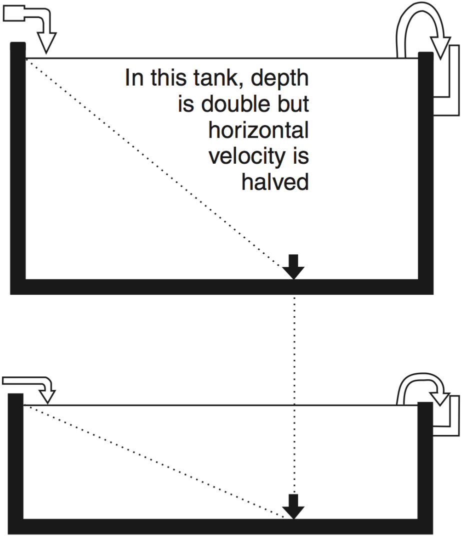
Concept: the ideal rectangular settling basin



- Inlet zone: feed is assumed to be uniformly distributed across the tank's cross-section (if viewed from the top)
- Settling zone: where particles move downwards towards the sludge area; particles also move horizontally due to fluid flow
- Outlet zone: the supernatant/clarified liquid is collected along the basin's cross section and removed in the *overflow*
- Sludge zone: where the solids collect and are removed in the tank's *underflow*

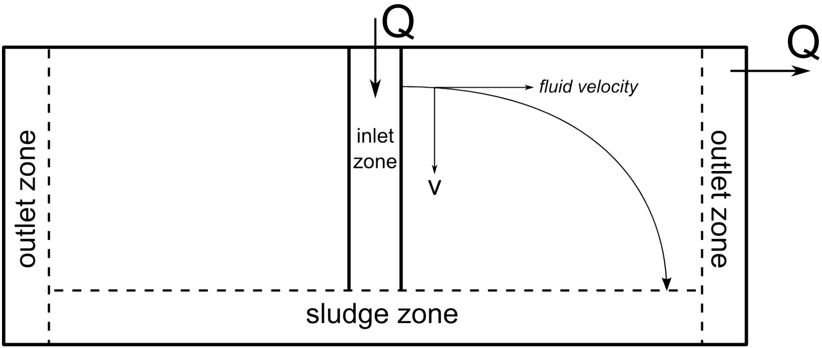
Ensure horizontal fluid velocity (i.e. residence time) is slow enough that particles at their terminal velocity, v, will reach the sludge zone and settle out.

The ideal rectangular settling basin



Changing depth has no effect in a rectangular basin [Svarovsky, 4ed, p170]

Concept: the ideal circular settling basin



fluid velocity is not constant; has a radial profile

- Same zones as before
- Fluid's horizontal velocity is a function of radial distance
- As before, ensure residence time is long enough for particles to reach the sludge zone

Settler design rules of thumb: size

For wastewater treatment the **main design criterion**: solids percentage in underflow

- A volume and mass balance on solids and liquids is then used to find the liquid overflow rate
- surface overflow rate (SOR) $\sim 40\text{m}^3$ per day per m^2 for primary units
- secondary units as low as 12 up to 30m^3 per day per m^2
- minimum depth of sedimentation tanks is around 3.0 m
- circular sedimentation: minimum diameter of 6.0 m
- length to width ratio of 5:1

Settler design rules of thumb: residence time

- gravity sedimentation tanks normally provide for 2 hour retention of solids, based on average flow
- longer times for light solids, or in winter times
- organic solids generally will not compact to more than 5 to 10%
- inorganic solids will compact up to 20 or 30%
- why important: we have to design sludge pumps to remove the solids: high concentration solids require diaphragm pumps

Capital costs considerations

Svarovsky 3rd, p179: cost $= ax^b$

- $x =$ tank diameter between 10 and 225 ft
- $a = 147$ and $b = 1.38$ for thickeners

Perry, 8ed, section 18.6

- Installation costs will be at least 3 to 4 times the actual equipment costs.
- Equipment items must include:
  - rakes, drivehead and motors
  - walkways and bridge (center pier) and railings
  - pumps, piping, instrumentation and lift mechanisms
  - overflow launder and feed

  Installation is affected by:
  - site surveying
  - site preparation and excavation
  - reinforcing bar placement
  - backfill

Operating costs

These are mostly insignificant

- e.g. 60 m (200 ft) diameter thickener, torque rating $= 1.0$ MN.m: requires ~ 12 kW
- due to slow rotating speed: peripheral speed is about 9 m/min
- implies low maintenance costs
- little attention from operators after start-up
- chemicals for flocculation (if required), frequently dwarfs all other operating costs [Perry, 8ed, Ch18.6]

Further self-study

- Designs with peripheral inlets (submerged-orifice flow control) and either center-weir outlets or peripheral-weir outlets adjacent to the peripheral-inlet channel.
- Deep cone thickener
- Lamella (inclined plate or tubes): often for gas-solid applications

Practice question

1. Calculate the minimum area of a circular thickener to treat 720 m^3 per hour of slurry containing 65μm particles of silica, whose density is about 2600 $kg.m^{-3}$. The particles are suspended in water at a concentration of 0.650 $kg.m^{-3}$. Use an over-design factor of 1.5 on the settling velocity.
   [Ans: $v = 3.7/1.5$ $mm.s^{-1}$ and $A = 81.4$ m^2]
2. If it is desired to have an underflow density of 1560 kg solids per m^3 underflow; what is the underflow volumetric flow rate if total separation of solids occurs?
   [Ans: $Q_{\text{under}} = 0.3$ m^3 $solids.hr^{-1}$]
3. Calculate the separation factor.

References for this section

- Geankoplis, "Transport Processes and Separation Process Principles", 3rd or 4th edition, chapter 14
- Perry's Chemical Engineers' Handbook, 8th edition, chapter 18
- Richardson and Harker, "Chemical Engineering, Volume 2", 5th edition, chapter 3 and 5
- Sinnott, "Chemical Engineering Design", Volume 6, 4th edition.
- Talmage and Fitch, 1955, "Determining Thickener Unit Areas", *Ind. Eng. Chem.*,**47**, 38-41, DOI:10.1021/ie50541a022
- Fitch, 1965, "Current theory and thickener design", *Ind. Eng. Chem.*, **57**, p 18-28, DOI:10.1021/ie50682a006
- Svarovsky, "Solid Liquid Separation", 3rd or 4th edition. Particularly thorough regarding the settler's mechanical accessories: pumps, scrapers, *etc.*