Separation Processes

ChE 4M3

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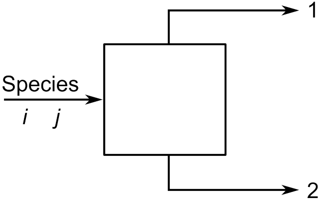
Last class: Separation factor

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 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

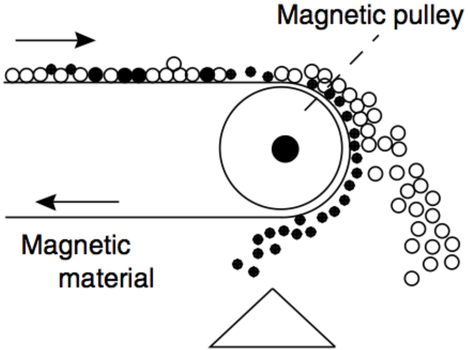
There are also others that go in this category. Deserving a quick mention are:

- 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

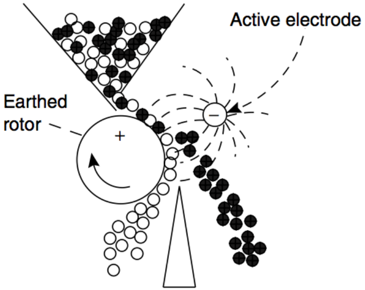
[Sinnott, 4ed, v6, Ch10]



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)
-
-
-
-
-
-

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 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

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

Drag force

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

where

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

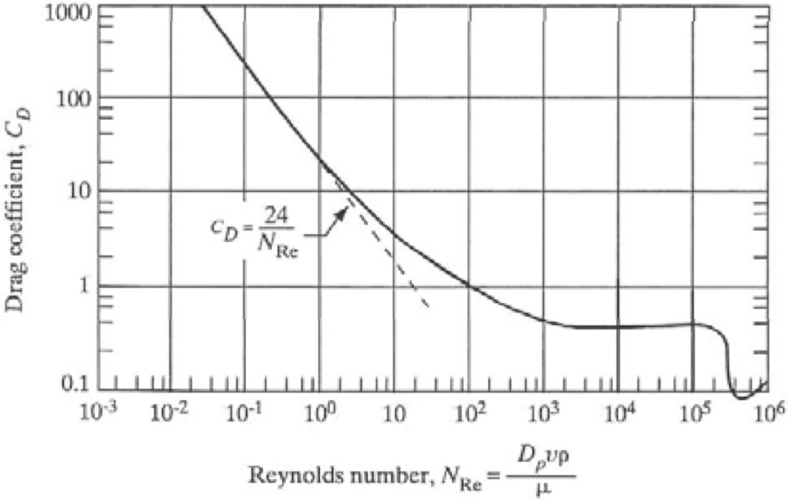
Estimating the drag coefficient, C_D

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)

$$m\frac{dv}{dt} = F_{\text{gravity}} - F_{\text{buoyancy}} - F_{\text{drag}} = 0 \qquad \text{at steady state}$$

$$0 = V_p\rho_p g - V_p\rho_f g - C_D A_p \frac{\rho_f v^2}{2}$$

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 $C_D = fn(\text{Re}) = fn(v)$

1. Assume $\text{Re} < 1$ (Stokes' region)
2. Solve for v using equation on slide 20
3. Calculate Reynolds number, $\text{Re} = \dfrac{D_p v \rho_f}{\mu_f}$
4. Was Reynolds number region assumption true? If so: stop.
5. If not, use new Re and recalculate C_D (see slide 17)
6. Repeat from step 2 to 5 until convergence

Example: A particle 1mm in diameter, with density of 5000 $\dfrac{\text{kg}}{\text{m}^3}$ 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

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
How to deal with this issue?

Video of sedimentation experiments

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

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
- 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*.