Separation Processes:
Cyclones
ChE 4M3

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http://learnche.mcmaster.ca/4M3

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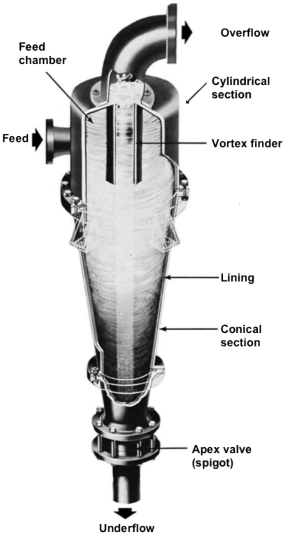
References*

- Svarovsky, "Solid Liquid Separation", 3rd or 4th edition, chapter 6.
- Richardson and Harker, "Chemical Engineering, Volume 2", 5th edition, chapter 1.
- Sinnot, "Chemical Engineering, Volume 6", 4th edition, chapter 10.
- Perry's Chemical Engineers' Handbook, 8th edition, chapter 17.2, "Gas-Solid Separations"
- Schweitzer, "Handbook of Separation Techniques for Chemical Engineers", chapter 4-135.

* Most of the illustrations are taken from these references.

The (hydro)cyclone



Uses

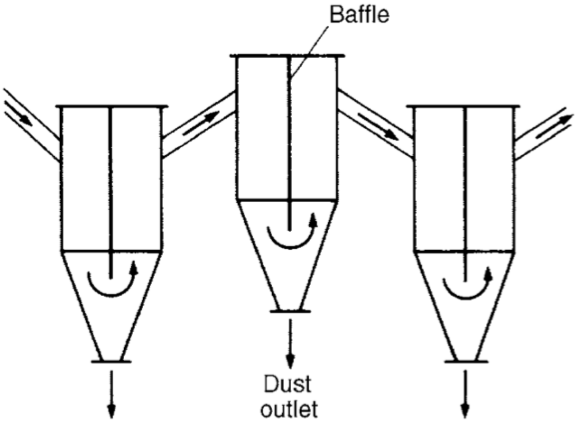
Wide variety of uses:

- dust removal (principal application) in many industries
  - cement industry
  - sawmills
  - catalyst particle recovery in reactors
- mist (droplets) removed from air streams
- recovery of spray-dried particles
- separating immiscible liquids (different densities)
- dewater suspensions: concentrate the product
- remove dissolved gases from liquid stream
- solids-solids separation: very common in mining

Where possible, consider a cyclone before a centrifuge for solid-fluid separations.

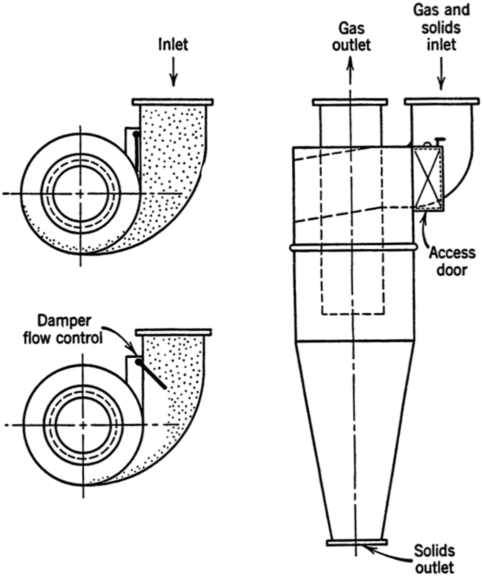
Alternatives

A number of alternatives exist; based on the principle of removing the particle's momentum relative to the fluid's momentum. Other options?



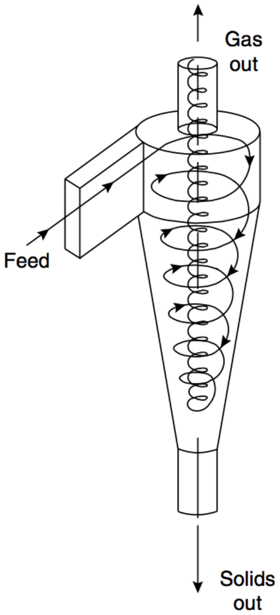
[Richardson and Harker, 5ed, p81]

Cyclone operation



[Brown and Associates, Unit Operations, p 119]

General path of travel in a cyclone low viscosity, low solids concentration



Generally, flow pattern is more complex than this.

See, for example, this video of a PET scan of a radioactive isotope labelled particle ^{18}F

- Vortex and tangential forces formed by the fluid

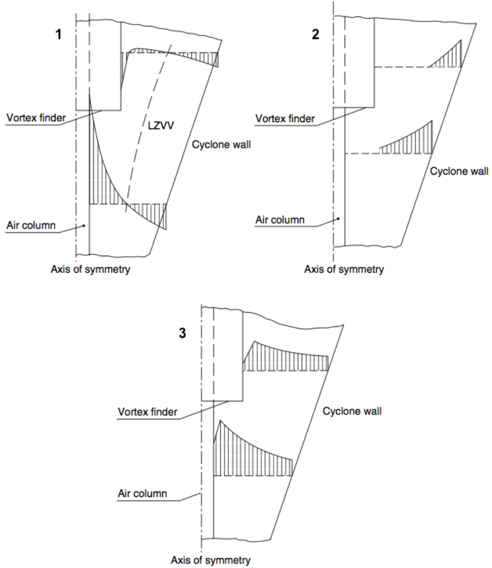
Principle of operation

- Same principle as a centrifuge: **density difference required**
- No moving parts! and no consumable components!
- Low operating costs: essentially only pay for ΔP
- Operated at many temperatures and pressures
- As small as 1 to 2cm to 10m in diameter
- Very low capital costs: can be made from many materials
- Particle sizes 5μm and higher are effectively removed
- Even different particle shapes (due to different settling velocities) can be separated
- Forces acting on particles: between 5 (large cyclones) and 2500 G (small cyclones)

Videos:

- http://www.youtube.com/watch?v=2bUlytvimy4
- http://www.youtube.com/watch?v=GxA49uVP2Ns
- http://www.youtube.com/watch?v=BicR3JGIE5M
- http://www.youtube.com/watch?v=QfTZUMq-LGI
- and many other videos of people making their own cyclones.

Velocity profile: *very complex*



3 directions of travel:

1. LZVV = locus of zero **vertical** velocity (axial $\updownarrow$)
2. **radial** velocity is small ($\longleftrightarrow$)
3. **tangential** velocity
   - $v_t r^n$ = constant
   - true at all heights inside cyclone

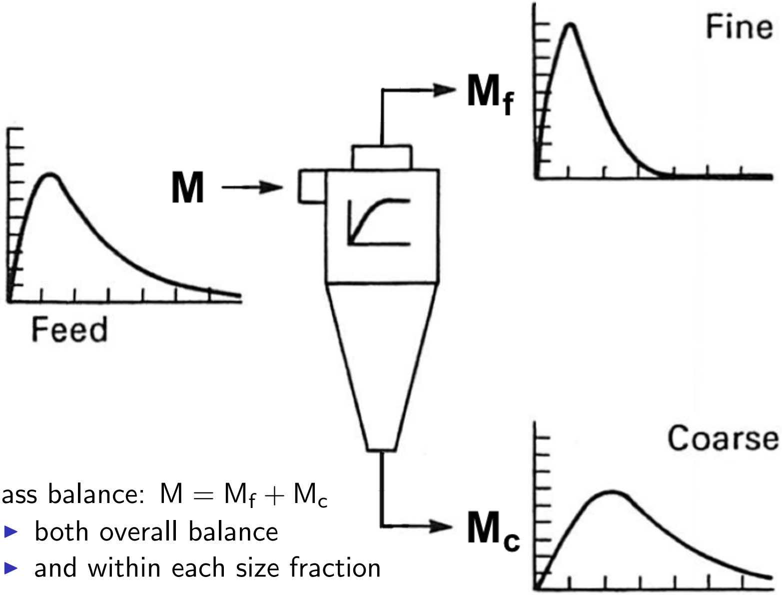
- centrifugal force (acts $\longrightarrow$)
- drag force (acts $\longleftarrow$)
- if $F_{\text{centrifugal}} > F_{\text{drag}}$ particle moves towards wall
- then pulled down in axial stream and exits in underflow

Velocity profiles

The above description is extremely simplistic; velocity profiles cannot be theoretically derived for most practical cases.

- it is **not** *gravity* that removes the heavier particles in underflow
- it is the slower, boundary layer flow at the walls and air flow out of the spigot
- particles rotate at a radius where centrifugal force is balanced by drag force (recall elutriation concept)
- larger, denser particles move selectively towards the wall
- residence time must be long enough to achieve equilibrium orbits; spiral patterns help
- all of this comes down to a careful balance of radial and tangential velocities
- velocities: these are our degrees of freedom to adjust the cyclone's performance

Evaluating a cyclone's performance



Mass balance: $M = M_f + M_c$

- both overall balance
- and within each size fraction

[Svarovsky, 3ed, p210]

Concept: Grade efficiency

Total efficiency

$$E_T = \frac{\mathrm{M_c}}{\mathrm{M}} = 1 - \frac{\mathrm{M_f}}{\mathrm{M}}$$

- not too much to interpret here: it is just a definition
- 0% efficiency: all mass is being sent to overflow (fines) stream
- 100% efficiency: all mass to underflow (coarse) stream

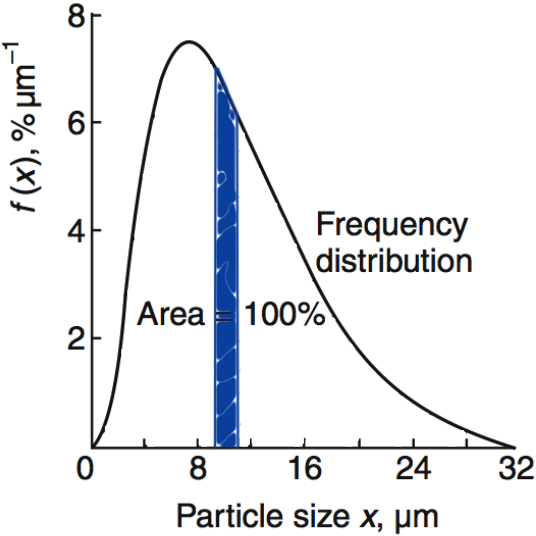
More useful though is

Grade efficiency

$$G(x) = \frac{(\mathrm{M_c})(\text{fraction of size } x \text{ in stream C, coarse stream})}{(\mathrm{M})(\text{fraction of size } x \text{ in feed})}$$

- calculated for a given particle size fraction x; repeat at all x's

What is "fraction of size x" again?



Percentage area under the (differential) curve, at size fraction x.

Back to grade efficiency

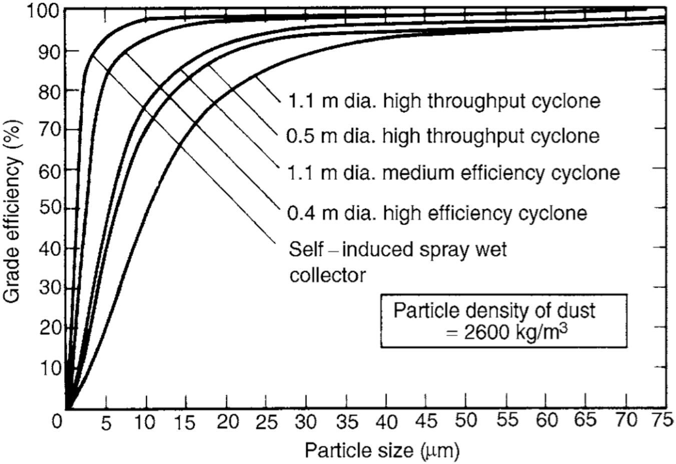
Grade efficiency equation

$$G(x) = \frac{(\mathrm{M_c})(\text{fraction of size } x \text{ in stream C, coarse stream})}{(\mathrm{M})(\text{fraction of size } x \text{ in feed})}$$

- If $G(x) = 0.5$ (50%): implies half the material (by mass) in size fraction x is leaving in the underflow (coarse)
- and the other half in the overflow; 50-50 (mass) split in the two outlets for particles of size x. Called the "cut size", x_{50}
- If $G(x) = 1.0$: implies the particle size that gets captured 100% in the coarse (underflow) stream
- Where $G(x)$ reaches 1.0 means the $x =$ *largest particle size* we expect to ever see in overflow (see next slide)
- (advanced)What would $G(x \to 0) = 10\%$ mean?
  [i.e. the $G(x)$ curves don't always reach 0%]

Grade efficiency curve

Calculate efficiency at each size fraction, x, and plot it:



Which is a more desirable cyclone from a separation efficiency perspective? In general, **what shape** would be the most desirable?

Day-to-day operation

- most important factor: pressure drop = ΔP = difference between inlet and *overflow* (fines) pressures and typically we have $\Delta P \sim 500$ to 1500 Pa
- increase ΔP, increases efficiency, E_T, and recovery into the coarse stream
- $\Delta P \propto \rho_f \qquad \Delta P \propto v_{\text{in}}^2$ and $v_{\text{overflow}}^2 \qquad \Delta P \propto \dfrac{1}{d_{\text{under}}}$
- v_{in} = entry velocity and d_{under} = diameter of underflow
- efficiency drops off at high solids concentration: try to operate as dilutely as possible if requiring high solids recovery
- leave the underflow opening diameter, d_{under}, as an physically adjustable variable: it is hard to predict its size from theory
- air leaks at this point are disastrous for efficiency [Perry, Ch 17.2, 8ed]

Operational advantages and disadvantages

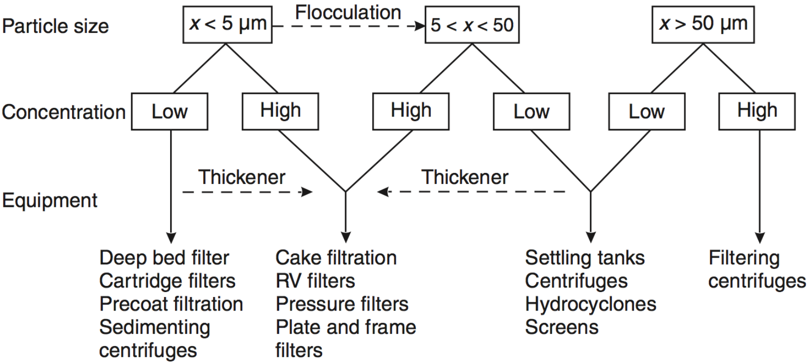
Advantages

- cost of operation: related to ΔP (i.e. electrical cost only)
- cheap capital cost to build cyclones
- small size
- mounted in any orientation (except for very large units)
- versatile: multiple uses

Balanced by some disadvantages:

- subject to abrasion
- cannot use a flocculated feed: high shear forces break flocs up
- limits on their efficiency curves
- requires consistent feed rate and concentration to maintain efficiency i.e. not suitable for variable (volumetric) feeds
  - counteract: use many small cyclones in parallel; bring them online as needed

Selection of cyclones, sedimentation or centrifuges



How to select/model cyclones

Given the complex fluid patterns, cyclone selection is best done with the vendor.

There are some guiding equations though.

$$\text{Eu} = \frac{\text{pressure forces}}{\text{inertial forces}} = \frac{\Delta P}{\rho_f v^2/2}$$

For a cyclone, the characteristic velocity, $v = \dfrac{4Q}{\pi D_{\text{cyc}}^2}$

ΔP	=	pressure drop from inlet to *overflow*	[Pa]
v	=	characteristic velocity (**not** inlet velocity)	[m.s^{-1}]
ρ_f	=	density of fluid	[kg.m^{-3}]
Q	=	volumetric feed flow rate	[$\text{m}^3\text{.s}^{-1}$]
D_{cyc}	=	cylindrical section diameter of cyclone	[m]

$0.02 < D_{\text{cyc}} < 5.0$ m are typical values

Euler number for cyclones

- It is relatively constant, under different flow conditions, for a given cyclone
- e.g. "this cyclone has an Euler number of 540"
- provided solids concentration remains around or below $1\ \text{g.m}^{-3}$
- Eu can be easily calculated found from clean air at ambient conditions

[Svarovsky]

If you can't get/calculate it, then use this:

$$\text{Eu} = \pi^2 \left(\frac{D_{\text{cyc}}}{L}\right) \left(\frac{D_{\text{cyc}}}{K}\right) \left(\frac{D_{\text{cyc}}}{M}\right)^2$$

$$\begin{aligned} L &= \text{width of rectangular inlet} && [\text{m}] \\ K &= \text{height of rectangular inlet} && [\text{m}] \\ M &= \text{diameter of overflow (gas) outlet} && [\text{m}] \end{aligned}$$

Predicting cut size

The cyclone's cut size, x_{50}, can be predicted from the Stokes number. This is a great way to scale-up through geometrically similar cyclones:

$$\mathrm{Stk}_{50} = \frac{x_{50}^2 \ \rho_S \ v}{18 \ \mu_f \ D_{\mathrm{cyc}}}$$

x_{50}	=	cut size	[m]
ρ_S	=	solids density	[kg.m^{-3}]
v	=	characteristic velocity	[m.s^{-1}]
μ_f	=	fluid viscosity	[Pa.s]
Stk_{50}	=	Stokes number	[–]

Note:

- this only predicts the cut-size, not the shape of the grade efficiency curve
- as with Eu, the Stk_{50} must be calculated on an actual feed
- it is relatively constant for changing conditions

Example

Outline the process/plan to solve this problem (do calculations at home!)

What diameter of cyclone do we need to treat 0.177 $m^3.s^{-1}$ of feed, given:

- $\mu_f = 1.8 \times 10^{-5}$ Pa.s
- $\rho_f = 1.2$ kg.m^{-3}
- $\rho_S = 2500$ kg.m^{-3}
- $\Delta P = 1650$ Pa
- x_{50} desired is 0.8 μm
- Eu $= 700$
- $\text{Stk}_{50} = 6.5 \times 10^{-5}$

Hint: if we use 1 cyclone, the pressure drop will be too high; so we must split the feed into multiple, *parallel* cyclones. So then, **how many cyclones**, and of **what diameter** should we use?

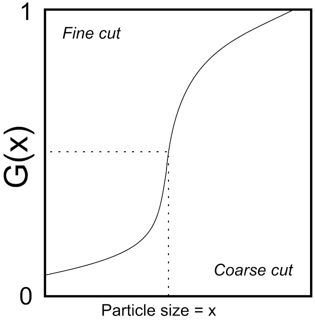
[*Ans*: 5 cyclones, $D_{\text{cyc}} = 0.15$m]

Circuits of separators

The remaining slides can be applied to any separation system, though most commonly used for cyclones and other solid-fluid separations.

When one unit is not enough...

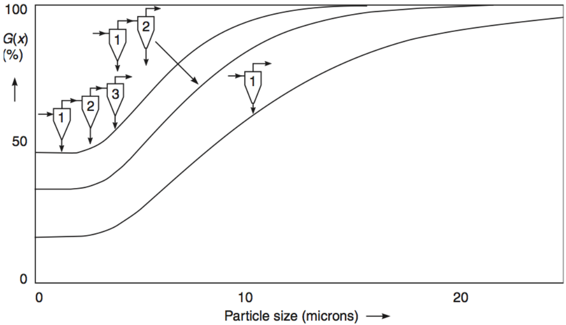
- we need a lower cut size
- need a sharper cut (slope of grade efficiency curve at x_{cut})
- we need high concentrations
- use lower velocities to reduce abrasion on equipment, but this will change efficiency, so then ...



The rest of this section is from Svarovsky, 4ed, chapter 16

Units in series: overflow

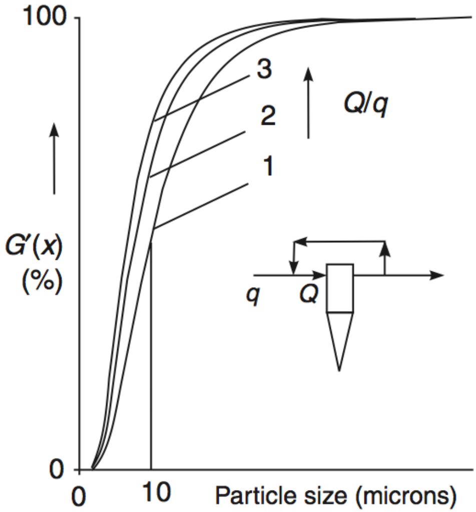
Grade efficiency curve for the entire sequence



- cut size becomes smaller with more units in series
- cut size sharpness (steepness of curve) increases
- but there are diminishing returns after 3 to 4 units

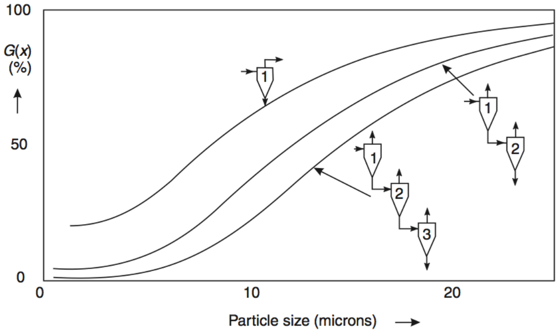
$G(x \to 0) = 10\%$: implies that 10% of the smallest size fractions are always found in the coarse underflow: we cannot remove these fines

Recycle around a unit



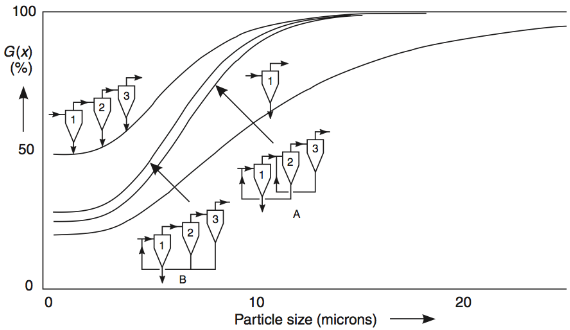
- dilutes feed, which improves efficiency
- decreases cut size for increasing recycle ratio: Q/q
- again diminishing returns after a ratio of 3 is exceeded

Units in series: underflow



- we get worse efficiency
- is this useful for anything?

Recycle in the underflow



- Best of both worlds?