Separation Processes

ChE 4M3

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- if you let us know about **any errors** in the slides
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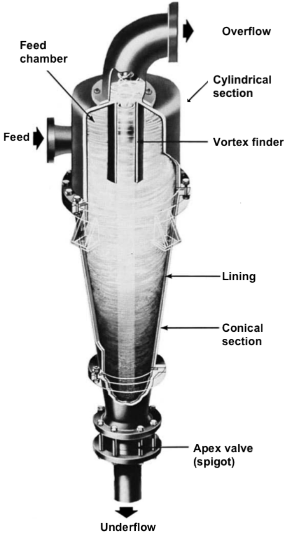
References

- 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.

The cyclone

Cyclone



Hydrocyclone

Uses

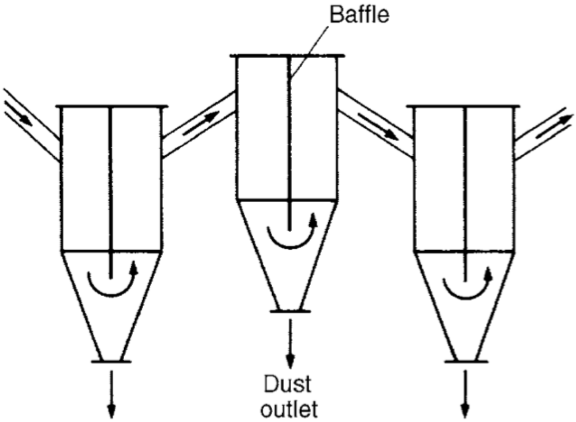
Wide variety of uses:

- 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.

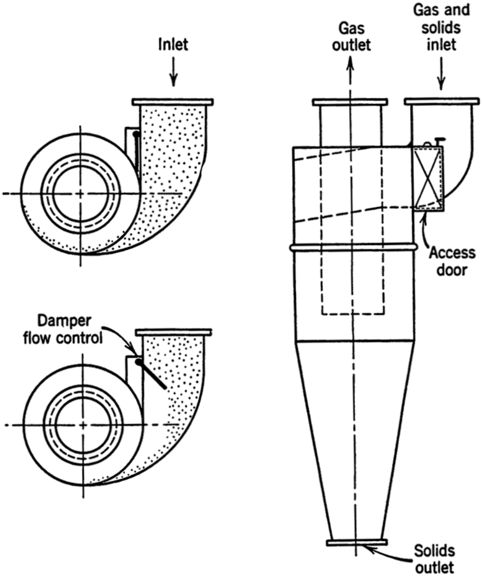
Alternatives

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



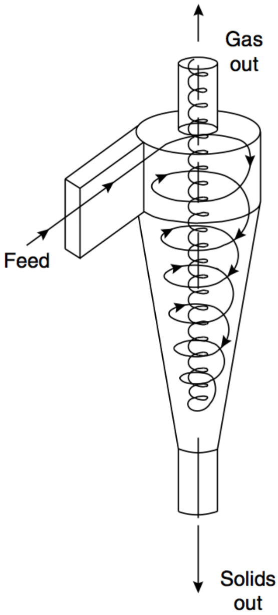
[Richardson and Harker, 5ed, p81]

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

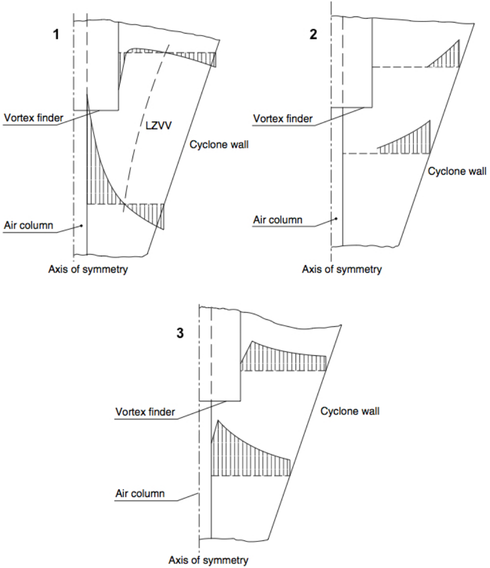
Principle of operation

- Same principle as a centrifuge: **density difference required**
- No moving parts!
- Very 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

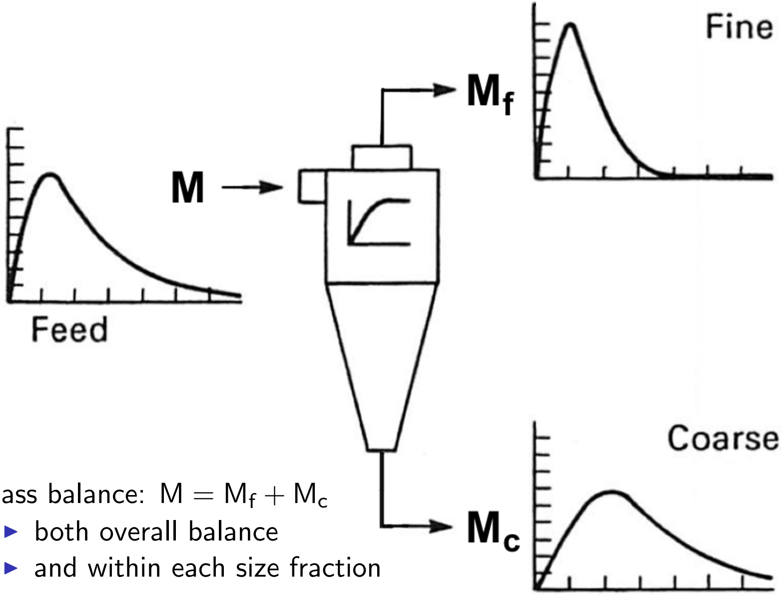
- centrifugal force (acts $\longrightarrow$)
- drag force (acts $\longleftarrow$)
- if $F_{\text{centrifugal}} > F_{\text{drag}}$ particle moves towards wall
- then pulled down in axial stream and exits in underflow

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
- 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 defined

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

- 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

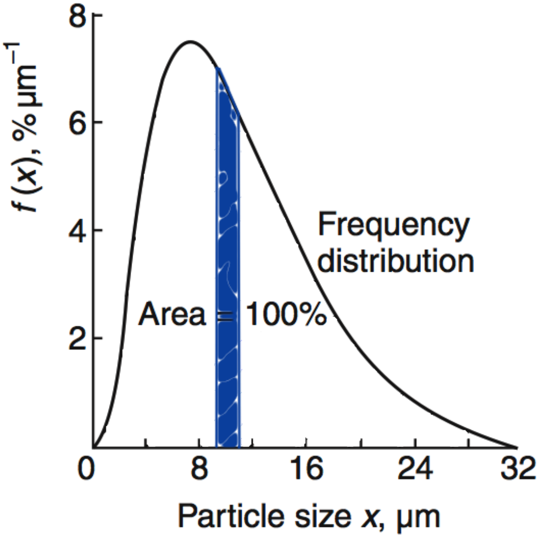
More useful though:

Grade efficiency defined

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

- calculated at a given particle size fraction x

"What is particle size fraction x?"



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

Back to grade efficiency

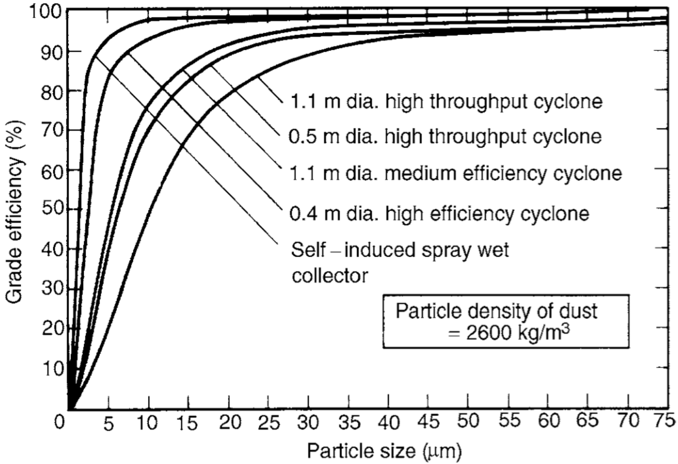
Grade efficiency

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

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

Grade efficiency curve

Calculate efficiency at each size fraction and plot it:



Which is a better cyclone?

Day-to-day operation

- most important factor: pressure drop $= \Delta P =$ difference between inlet and *overflow* pressures
- increase ΔP, increases efficiency
- $\Delta P \propto \rho_f \qquad \Delta P \propto u_{\text{in}}^2$ and $u_{\text{overflow}}^2 \qquad \Delta P \propto \dfrac{1}{d_{\text{under}}}$
- u_{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 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
- 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