Separation Processes

ChE 4M3

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Overall revision number: 153 (November 2012)

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We appreciate:

- if you let us know about **any errors** in the slides
- **any suggestions to improve the notes**

All of the above can be done by writing to

`kevin.dunn@mcmaster.ca`

If reporting errors/updates, please quote the current revision number: 153

Administrative

- Assignment 5 is posted (3 questions so far); questions 4 and 5 posted by Tuesday afternoon
- Assignment 5 is due in the Chem Eng drop box by Monday, 03 December, at 16:00, or earlier.
- Assignment 4 will be available for pick up on Thursday and Friday.
- Midterm will be available to pick up Tuesday, Thursday, Friday.
- Please fill in a course evaluation: https://evals.mcmaster.ca
- Confused about grades? There's a grading spreadsheet online
  - Please do not use averages and symbols calculated by Avenue

- Course review on Friday, 30 November. ⟵ **Final class**

Background

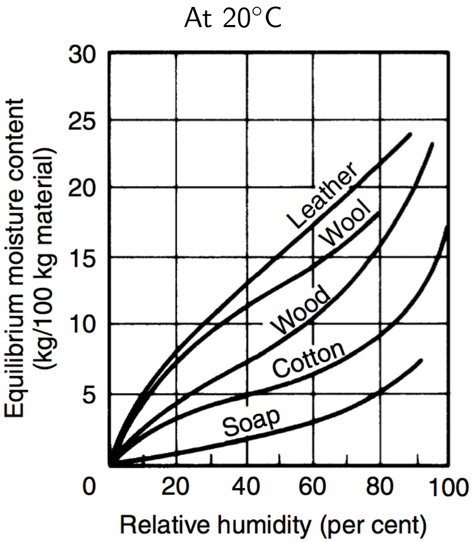
We consider **drying of solid products** here.

- Remove liquid phase from solid phase by an ESA = thermal energy
- It is the final separating step in many processes
  - pharmaceuticals
  - foods
  - crops, grains and cereal products
  - lumber, pulp and paper products
  - catalysts, fine chemicals
  - detergents

Why dry?

- packaging dry product is much easier than moist/wet product
- reduces weight for shipping
- preserves product from bacterial growth
- stabilizes flavour and prolongs shelf-life in foods
- provides desirable properties: e.g. flowability, crispiness
- reduces corrosion: the "corrosion triangle": removes 1 of the 3

The nature of water in solid material



Material, when exposed to air with a certain humidity, will reach equilibrium with that air.

1. **Bound moisture**
   - adsorbed into material's capillaries and surfaces
   - or in cell walls of material
   - its vapour pressure is below water's partial pressure at this T
2. **Free moisture**
   - water in excess of the above equilibrium water

[Richardson and Harker, p 902]

Drying: the heat and mass transfer view points

Both heat and mass transfer occur simultaneously

Mass transfer

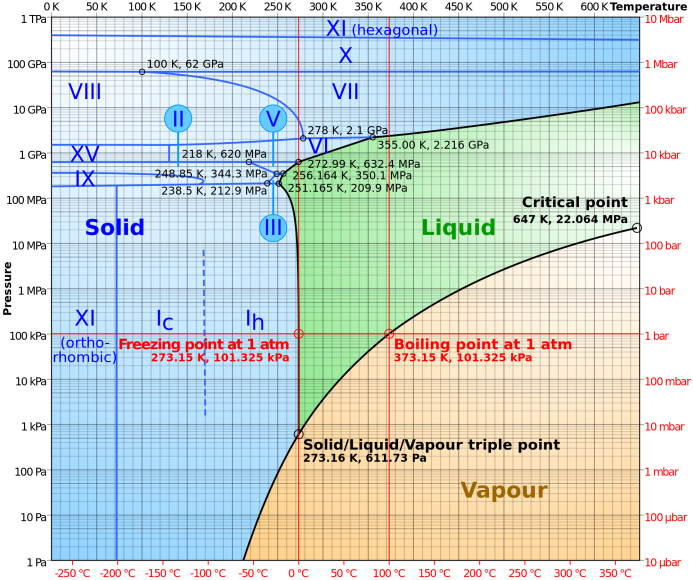
- Bring liquid from interior of product to surface
- Vapourization of liquid at/near the surface
- Transport of vapour into the bulk gas phase

Heat transfer from bulk gas phase to solid phase:

- portion of it used to vapourize the liquid (latent heat)
- portion remains in the solid as (sensible heat)

- Key point: heat to vapourize the liquid is provided by the air stream
- The ΔH_{vap} at a function of the temperature at which it occurs
  - 2501 kJ/kg at 0°C
  - 2260 kJ/kg at 100°C
  - Linearly interpolate over this range (small error though)

Terminology



[Wikipedia File:Phase_diagram_of_water.svg]

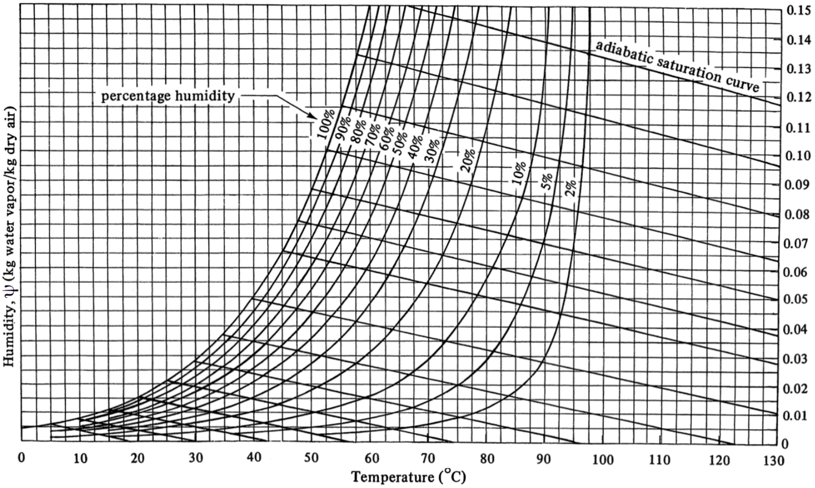
Terminology

- Partial pressure, recall, is the pressure due to water vapour in the water-air mixture
- Vapour pressure, is the pressure exerted by (molecules of liquid water in the solid) on the gas phase in order to escape into the gas [a measure of volatility]

Moisture evaporates from a wet solid only when its vapour pressure exceeds the partial pressure

- Vapour pressure can be raised by heating the wet solid

Psychrometric chart



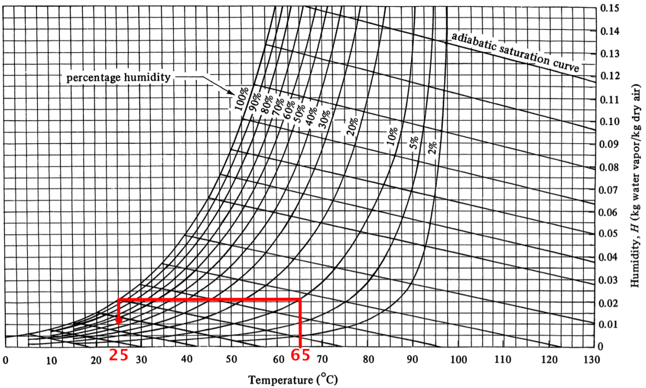
[Geankoplis, p568; multiple internet sources have this chart digitized]

Terminology

- Dry bulb temperature: or just T_{db} = "*temperature*" (nothing new here)
  - the horizontal axis on the psychrometric chart
- Humidity $= \psi =$ mass of water vapour per kilogram of dry air
  - units are $\left[\dfrac{\text{kg water vapour}}{\text{kg dry air}}\right]$
  - called H in many textbooks; always confused with enthalpy; so we will use ψ
  - units do not cancel, i.e. not dimensionless
  - the vertical axis on the psychrometric chart
- Maximum amount of water air can hold at a given T:
  - ψ_S = saturation humidity
  - move up vertically to 100% humidity
- Percentage humidity $= \dfrac{\psi}{\psi_S} \times 100$
- Partial pressure we said is the pressure due to water vapour in the water-air mixture
  - $\psi = \dfrac{\text{mass of water vapour}}{\text{mass of dry air}} = \dfrac{18.02}{28.97} \dfrac{p_A}{P - p_A}$
  - p_A = partial pressure of water in the air

Terminology

- Dew point: the temperature to which you must cool the air/vapour mixture to just obtain saturation (100% humidity), i.e. condensation just starts to occur.



Example: Air at 65°C and 10% humidity has a dew point temperature of 25°C. This parcel of air contains 0.021 kg of water per kilogram of dry air.

Terminology

- Humid heat: amount of energy to raise 1kg of air and the water vapour it contains by 1°C

$$c_S = 1.005 + 1.88\psi$$

  - c_S has units $\left[\dfrac{\text{kJ}}{(\text{kg dry air})(\text{K})}\right]$
  - $1.005 \left[\dfrac{\text{kJ}}{(\text{kg dry air})(\text{K})}\right]$ is heat capacity of dry air
  - $1.88 \left[\dfrac{\text{kJ}}{(\text{kg water vapour})(\text{K})}\right]$ is heat capacity of water **vapour**
  - ψ is the humidity $\left[\dfrac{\text{kg water vapour}}{\text{kg dry air}}\right]$

Administrative

Assignment 5

- Due on Monday, 03 December, at 16:00 in Chem Eng dropbox
- Or due electronically
- Update to question 3.3.3 (or question 3.3(c))
  - Solvent flow, $S = 27.5$ kg/hr, not 15 kg/hr
- Assignment 4 available for pick up

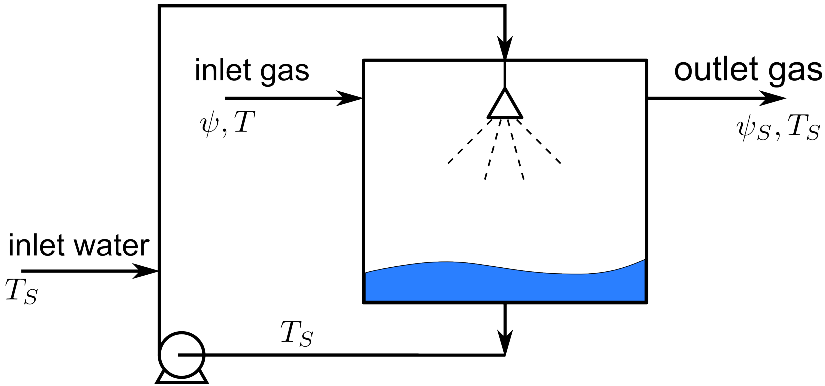
Please fill in a **course evaluation**:

https://evals.mcmaster.ca

- Currently 42% of the class have filled it in

Terminology: adiabatic saturation

Consider a stream of air at temperature T and humidity ψ. It contacts fine water droplets long enough to reach equilibrium. The leaving gas has temperature T_S and humidity ψ_S.

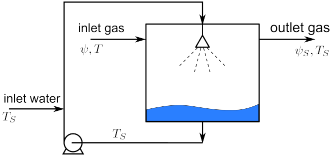


We expect outlet gas: $T_S < T$ and $\psi_S > \psi$

The energy to evaporate liquid water into the leaving air stream comes from the air.

Terminology: adiabatic saturation

Quantify it: do an enthalpy balance at $T_{\text{ref}} = T_S$ (i.e. disregard water)



Enthalpy of vapour phase entering:

$$c_S\,(T - T_S) + (\psi)(\Delta H_{\text{vap}})$$

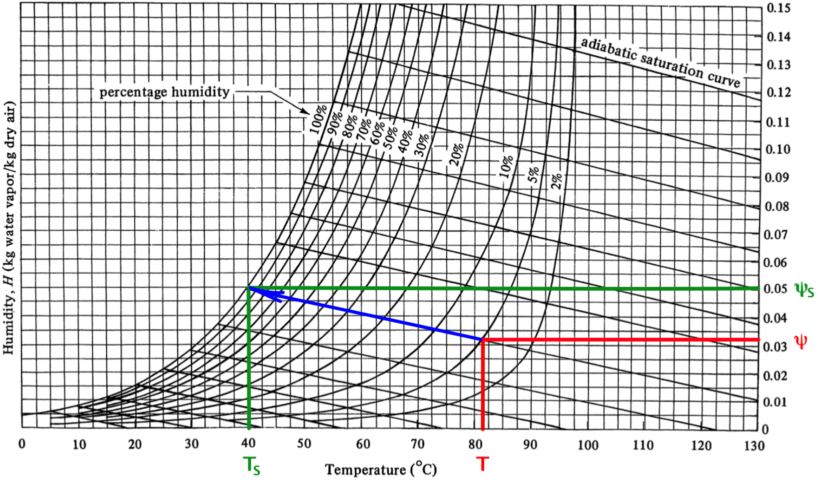
Enthalpy of vapour phase leaving:

$$c_S\,(T_S - T_S) + (\psi_S)(\Delta H_{\text{vap}})$$

$$\frac{y\text{-axis change}}{x\text{-axis change}} = \frac{\psi - \psi_S}{T - T_S} = -\frac{c_S}{\Delta H_{\text{vap}}} = -\frac{1.005 + 1.88\psi}{\Delta H_{\text{vap}}}$$

These are the diagonal sloped lines on the psychrometric chart: adiabatic saturation curves.

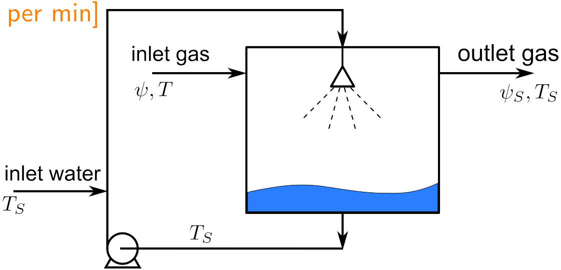
Adiabatic saturation temperature



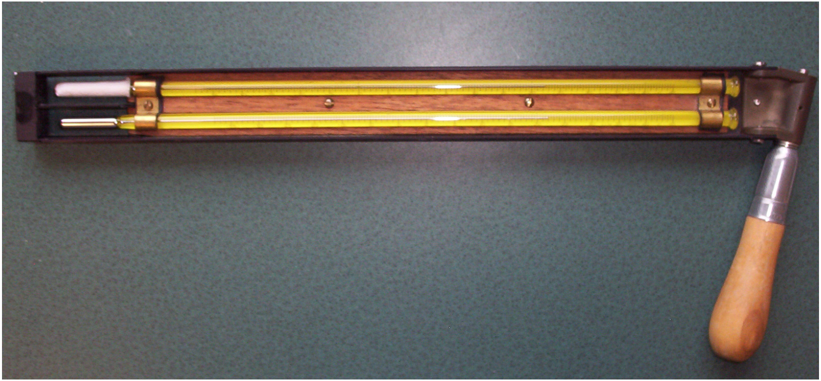
Exercise

An air stream at 70°C and carrying 0.055 kg water per kg dry air is adiabatically contacted with liquid water until it reaches equilibrium. The process is continuous and operating at steady-state. Air feed is 1 kg dry air per minute.

1. What is the percentage humidity of the incoming air stream? [20%]
2. What is the percentage humidity of the air stream leaving? [100%]
3. What is the humidity [mass/mass] of the air stream leaving? [66g/kg]
4. What is the temperature of the air stream leaving? [45°C]
5. If the contacting takes place in a unit shown below, what is the mass of inlet make-up water required at steady-state operation? [$(66 - 55) = 11$ g per min]



Wet-bulb temperature



[Wikipedia: http://en.wikipedia.org/wiki/Wet-bulb_temperature]

- Calculated similar to adiabatic saturation temperature, except the gas temperature and humidity do not change
- Surprisingly, the slope coefficient is very close to adiabatic slope coefficient
- This is only true for water vapour

Humid volume

Equivalent to the inverse density $1/\rho$ of moist air.

Derived from the ideal-gas law and simplified here:

$$v_H = \left[2.83 \times 10^{-3} + 4.56 \times 10^{-3}\psi\right] T_{\text{db}} \qquad \left[\frac{\text{m}^3}{\text{kg moist air}}\right]$$

- ψ is humidity in [kg water per kg dry air]
- T_{db} is the recorded dry bulb temperature in [K]

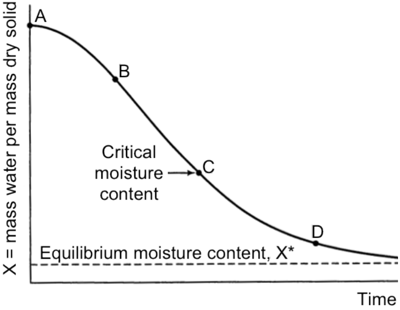
For example, 350K and $\psi = 0.026$ kg/kg, then

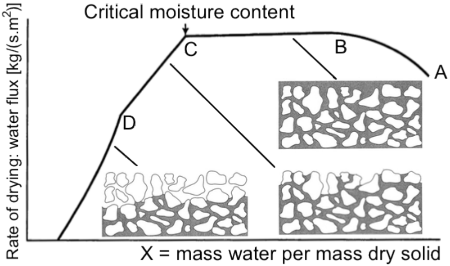
$$v_H = \left[2.83 \times 10^{-3} + 4.56 \times 10^{-3}(0.026)\right](350) = 1.03 \, \frac{\text{m}^3}{\text{kg moist air}}$$

Drying profiles

Solids drying is phenomenally complex for different materials.
Observe it experimentally and plot it:

[Seader, *et al.*, p 751 and 752]





- A → B: initial phase as solid heats up
- B → C: constant-rate drying
- C → D: first falling-rate drying
- D → end: second falling-rate drying

Drying profiles

- Water flux $= \dfrac{\text{mass of water removed}}{\text{(time)(area)}} = -\dfrac{m_s}{A}\dfrac{dX}{dt} = \dfrac{1}{A}\dfrac{d(m_w)}{dt}$
- X = mass of water remaining per mass dry solid
- A = surface area of solid exposed
- m_s = mass of dry solid
- m_w = mass of water evaporated out of solid

We are most interested in the constant drying-rate period:

- *rate-limiting step*: heat and mass transfer through boundary layer at the solid surface
- the solid is able to provide water to the surface a fast rate

Heat transfer during constant drying

- In constant-rate drying region the wet surface continually supplies moisture.
- All the heat provided is taken up to evaporate liquid

$$\begin{aligned}
(\text{Water flux})(\Delta H_{\text{vap}}) &= \text{Heat flux} \\
\frac{1}{A}\frac{d(m_w)}{dt} \times \Delta H_{\text{vap}} &= \frac{\text{driving force}}{\text{resistance}} = \frac{(T_{\text{air}} - T_{\text{solid surface}})}{1/h} \\
\frac{d(m_w)}{dt} &= \frac{(h)(A)(T_{\text{db}} - T_{\text{wb}})}{\Delta H_{\text{vap}}} \\
\int_{m_{w,0}}^{m_{w,f}} d(m_w) = \Delta M_{\text{water}} &= \int_{t_0}^{t_f} \frac{(h)(A)(T_{\text{db}} - T_{\text{wb}})}{\Delta H_{\text{vap}}}\, dt \\
\frac{(\Delta M_{\text{water}})(\Delta H_{\text{vap}})}{(h)(A)(T_{\text{db}} - T_{\text{wb}})} &= \text{time to remove } \Delta M_{\text{water}}
\end{aligned}$$

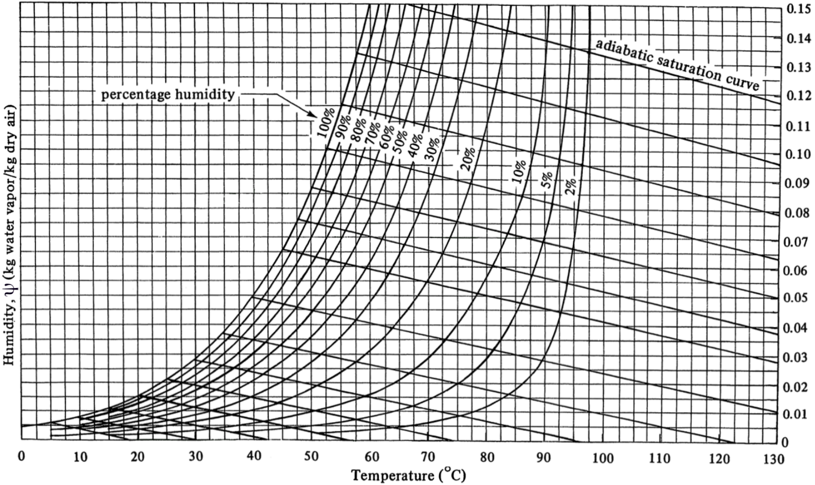
Some heat-transfer correlations for h

- In constant-rate drying region the wet surface continually supplies moisture
- Heat-transfer coefficients derived that are independent of solid type!

1. Parallel flow to surface:
    - Air between 45 to 150°C
    - $G = 2\,450$ to $29\,300\,\text{kg.hr}^{-1}.\text{m}^{-2}$
    - This corresponds to a velocity of $v = 0.61$ to 7.6m.s^{-1}
    - $G = 3\,600\,\rho v_{\text{avg}}$ where v and ρ are in SI units
    - $\mathbf{h} = \mathbf{0.0204G^{0.8}}$ $[\text{W.m}^{-2}.\text{K}^{-1}]$ $\longleftarrow$ awkward units for G!
2. Perpendicular flow (impingement)
    - Air between 45 to 150°C
    - $G = 3\,900$ to $19\,500\,\text{kg.hr}^{-1}.\text{m}^{-2}$
    - This corresponds to a velocity of $v = 0.9$ to 4.6m.s^{-1}
    - $\mathbf{h} = \mathbf{1.17G^{0.37}}$ $[\text{W.m}^{-2}.\text{K}^{-1}]$

See textbooks for **h** when using pelletized solids (e.g packed bed)

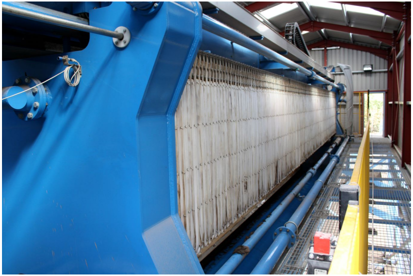
Why these equations makes sense



$$\frac{(\Delta M_{\text{water}})(\Delta H_{\text{vap}})}{(h)(A)(T_{\text{db}} - T_{\text{wb}})} = \text{time to remove } \Delta M_{\text{water}}$$

$$h = a(G)^b = a(\rho v)^b$$

Filter cake drying example



[Flickr, CC BY 2.0]

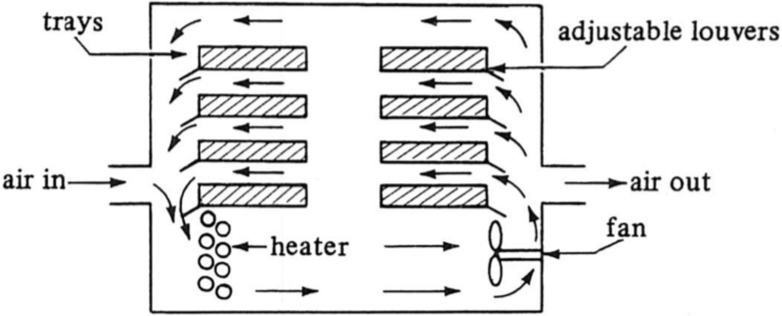
[Flickr, CC BY 2.0]

Consider 100kg of cake, discharged at 30% moisture (wet basis). Air to dry the cake at 75°C is used, 10% relative humidity, with a velocity of 4 m/s parallel to the solids in a tray dryer; the tray holds $2\,\mathrm{m}^2$. The aim is to achieve a 10% (dry basis) cake which can be milled and packaged.

Estimate the drying time.

Some equipment examples: Shelf/tray dryer

We will see more equipment examples next.



[Geankoplis, p 560]

Filter cake drying example

1. What is the humidity of the incoming air stream? [$\psi = 0.04$ kg water/kg dry air]
2. What is the wet-bulb temperature of this air stream? [$T_{\text{wb}} \approx 41.3^\circ$C]
3. What is the humid volume of the drying air stream? [$T_{\text{db}} = 348$K, $v_H = 1.048\text{m}^3/\text{kg}$]
4. Estimate the heat transfer coefficient.
   - $G = 3\,600\,\rho v_{\text{avg}} = 3\,600(1.048)^{-1} \times 4 = 13\,740\,\text{kg.hr}^{-1}.\text{m}^{-2}$
   - $h = 0.0204(13\,740)^{0.8} = h = 41.7\ \text{W.m}^{-2}.\text{K}^{-1}$
5. Substitute into the constant-drying rate expression to find:
   - drying time $= \dfrac{(\Delta M_{\text{water}})(\Delta H_{\text{vap}})}{hA(T_{\text{db}} - T_{\text{wb}})} = \dfrac{(23)(2401 \times 1000)}{(41.7)(2)(75 - 41.3)} =$ **5.46 hrs**
   - Water initially $= 30$ kg; dry basis $= 0.1 = \dfrac{30 - \Delta M_{\text{water}}}{70\,\text{kg dry solids}}$
   - We need the ΔH_{vap} at T_{wb} (why?) [2401 kJ/kg]
     - 2501 kJ/kg at 0°C
     - 2260 kJ/kg at 100°C

Equipment

Multiple dryer types are commercially available:

- each have relative advantages and disadvantages
- our purpose is not to cover their details
- in practice: you would work in consultation with vendors
- in practice: plenty of trade literature on the topics (SDL*!*)

Some major distinctions though:

- **mode of operation**: batch (low volume) *vs* continuous
- how the **heat is provided**:
  - direct heat: convective or adiabatic; provides heat and sweeps away moisture
  - indirect heat: non-adiabatic, i.e. by conduction or radiation; e.g microwave (for flammables/explosives)
- **degree of agitation**
  - stationary material
  - fluidized or mixed in some way

How to choose the equipment*

- Strongly dependent of feed presentation
  - solid, slurry, paste, flowing powder, filter cake, fibrous, *etc*
- Heating choice: temperature-sensitive if convective heat is directly applied
- Agitation:
  - produce fines (dust hazard) or fragile material
  - good mixing implies good heat distribution
  - stationary product: can form hot-spots in the solid

General choices are between:

1. shelf/tray dryers
2. continuous tunnels
3. rotary dryers
4. drums
5. spray dryers
6. fluidized beds

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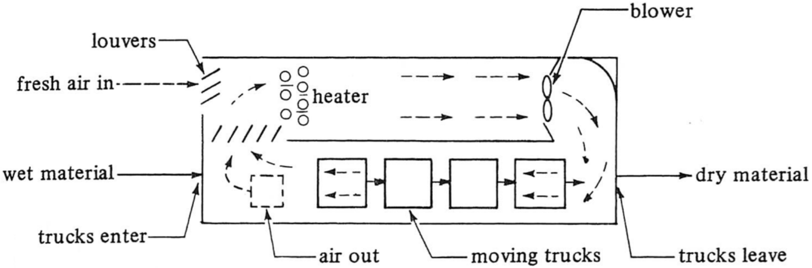
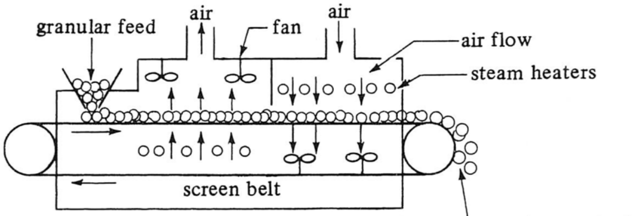
* See Schweitzer; See Perry's; See Seader, Henley and Roper

Some equipment examples: Continuous tunnel dryer



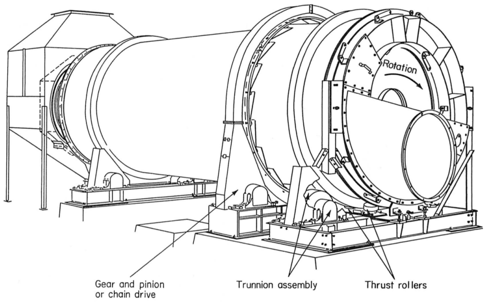
(a)



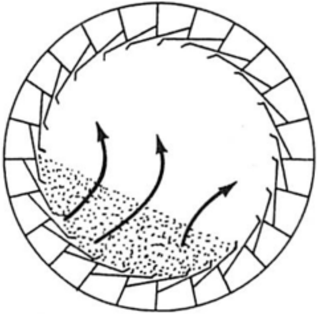
(b)

[Geankoplis, p 561]

Some equipment examples: Rotating dryer

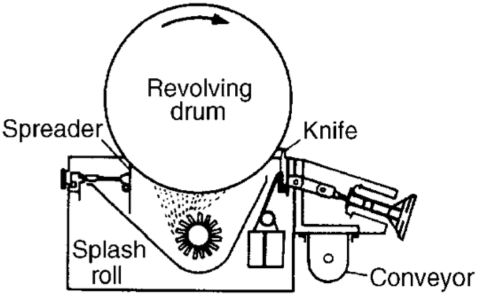


[Schweitzer, p 4-161 and 4-162]

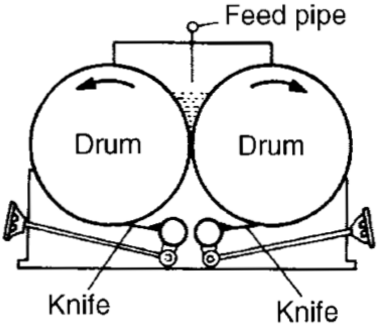


- 0.3 to 7 m in diameter
- 1.0 to 30 m in length
- 5 to 50 kg water evaporated per hour per m^3 dryer volume
- Residence time: 5 minutes to 2 hours

Some equipment examples: Drum dryers



Splash feed

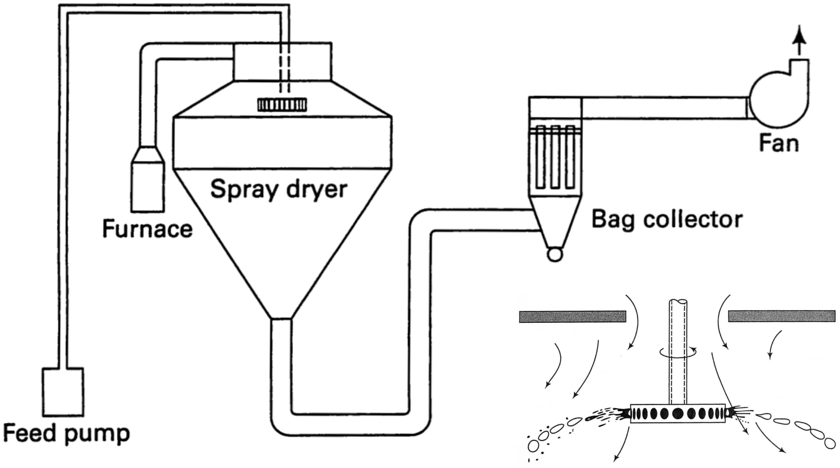


Double drum, top feed

[Richardson and Harker, p 932]

- Drums heated with condensing steam
- Dried material is scraped off in chips, flakes or powder

Some equipment examples: Spray dryers

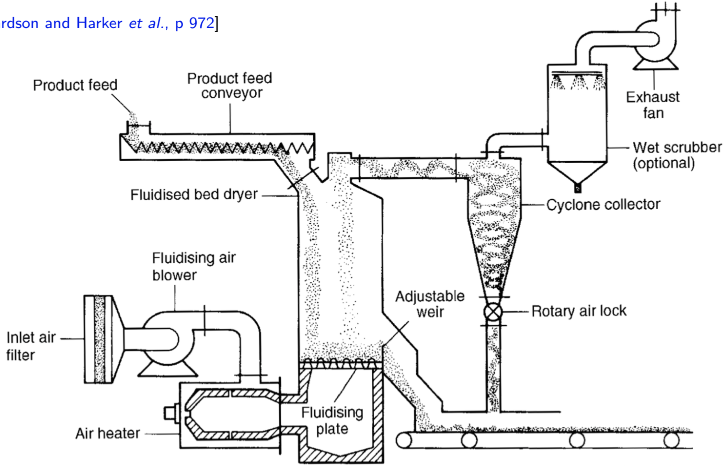


[Seader *et al.*, p 373]

- Also called atomizers
- Produce uniformly shaped, spherical particles
- e.g. milk powder, detergents, fertilizer pellets

Some equipment examples: Fluidized bed dryer

[Richardson and Harker *et al.*, p 972]



- upward flowing air stream (elutriation)
- turbulent mixing: good heat and mass transfer
- uniform solid temperature
- solids are gently treated
- solids are retrieved via gravity and cyclones
- fluidizing air scrubbed before vented

References used (in alphabetical order)

- Geankoplis, "Transport Processes and Separation Process Principles", 4th edition, chapter 09
- Perry's Chemical Engineers' Handbook, Chapter 12
- Richardson and Harker, "Chemical Engineering, Volume 2", 5th edition, chapter 16
- Schweitzer, "Handbook of Separation Techniques for Chemical Engineers", Chapter 4.10
- Seader, Henly and Roper, "Separation Process Principles", 3rd edition, chapter 18
- Uhlmann's Encyclopedia, "Drying", DOI:10.1002/14356007.b02_04.pub2