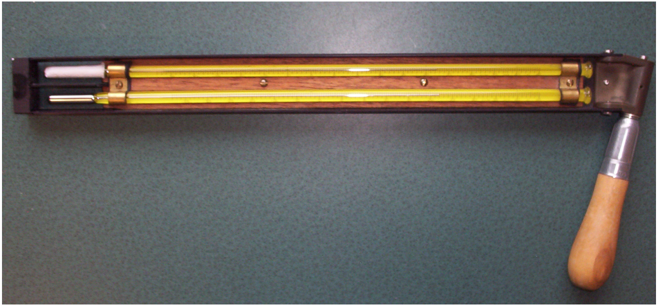
Wet-bulb temperature



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

- the *temperature* a parcel of air would have if it were cooled to saturation by evaporation of water into it, with the latent heat being supplied by the parcel
- Calculated in a manner similar to adiabatic saturation temperature (use the sample slopes - *for water only!*)
- the *temperature* we consider evaporation to be occurring at, on the particle's surface

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

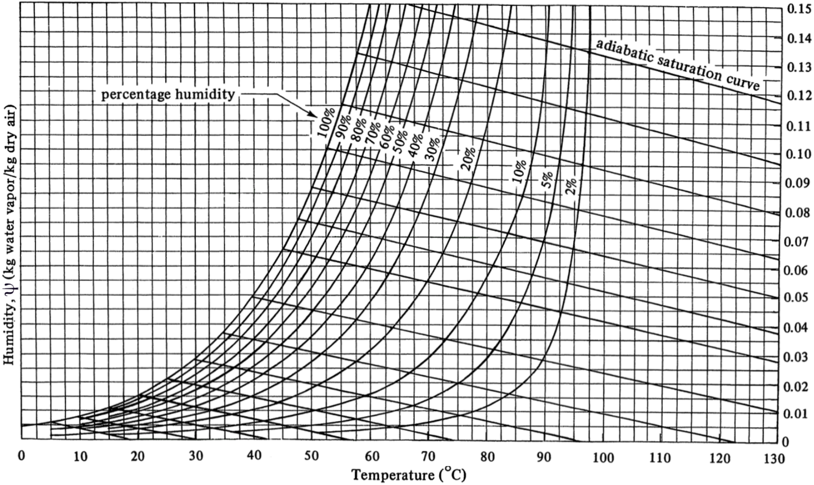
$$v_H = \left[2.83 \times 10^{-3} + 4.56 \times 10^{-3}(0.026)\right](350) = 1.03\,\frac{\text{m}^3}{\text{kg moist air}}$$

Example

Air at 55°C and 1 atm enters a dryer with a humidity of 0.03 kg water per kg dry air. What are values for:

- the recorded dry-bulb temperature
- percentage humidity
- dew point temperature
- humid heat
- humid volume
- wet-bulb temperature

Psychrometric chart



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

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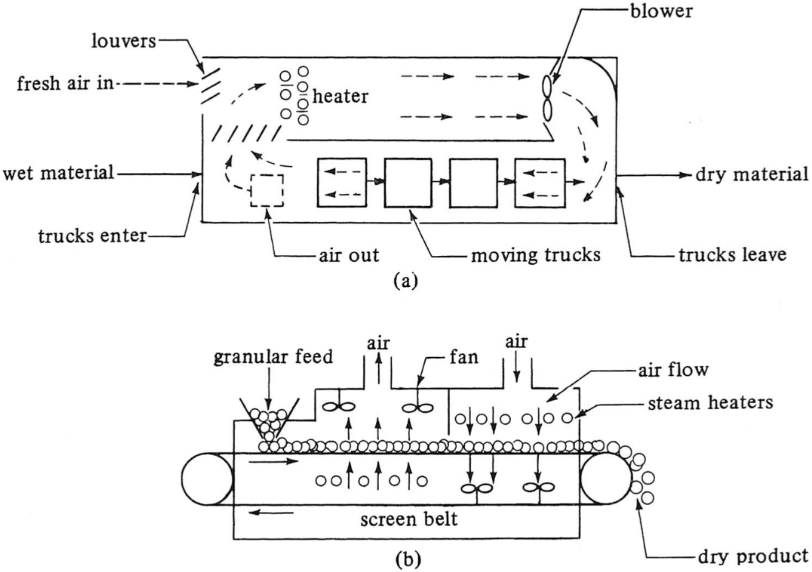
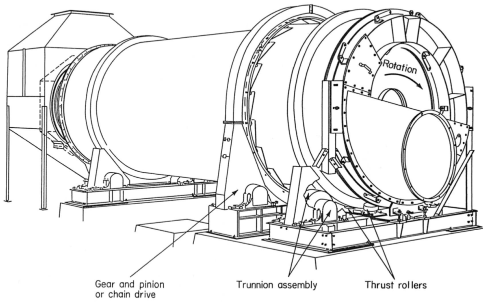
* See Schweitzer; See Perry's; See Seader, Henley and Roper

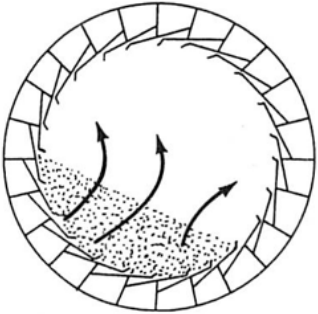
Some equipment examples: Continuous tunnel dryer



[Geankoplis, p 561]

Some equipment examples: Rotating dryer

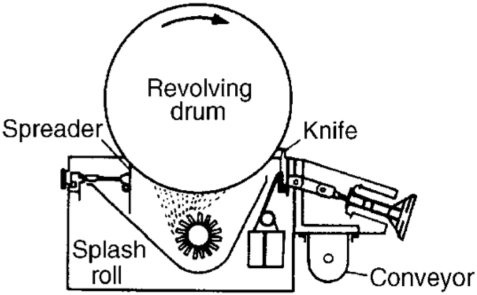




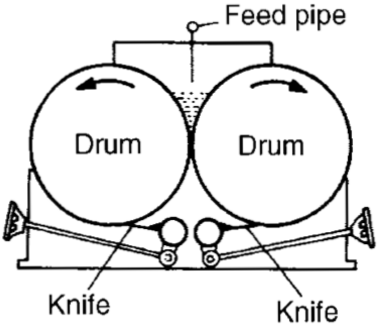
[Schweitzer, p 4-161 and 4-162]

- 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

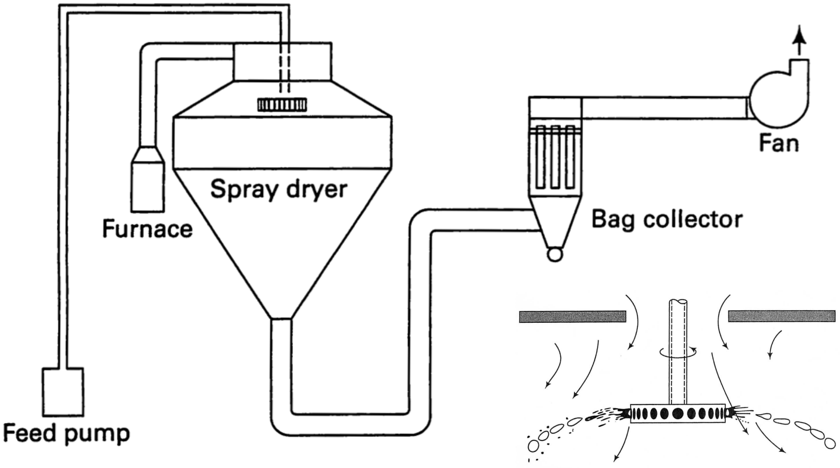


Double drum, top feed

[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

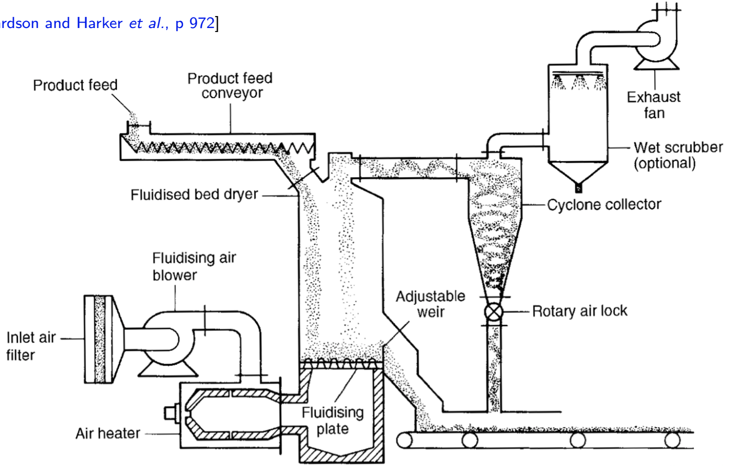


[Seader *et al.*, p 373]

- 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]

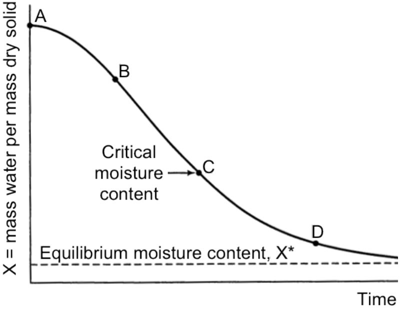


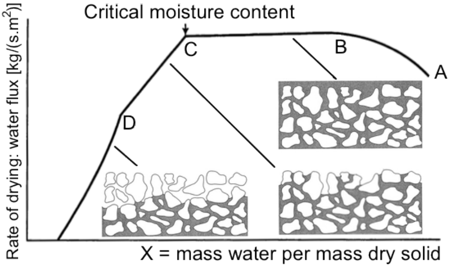
- upward flowing air stream (elutriation)
- turbulent mixing: good heat and mass transfer
- uniform solid temperature
- solids are gently treated
- solids are retrieved via gravity and cyclones
- fluidizing air scrubbed before vented

Drying profiles

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

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





- A $\rightarrow$ B: initial phase as solid heats up
- B $\rightarrow$ C: constant-rate drying
- C $\rightarrow$ D: first falling-rate drying
- D $\rightarrow$ 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!

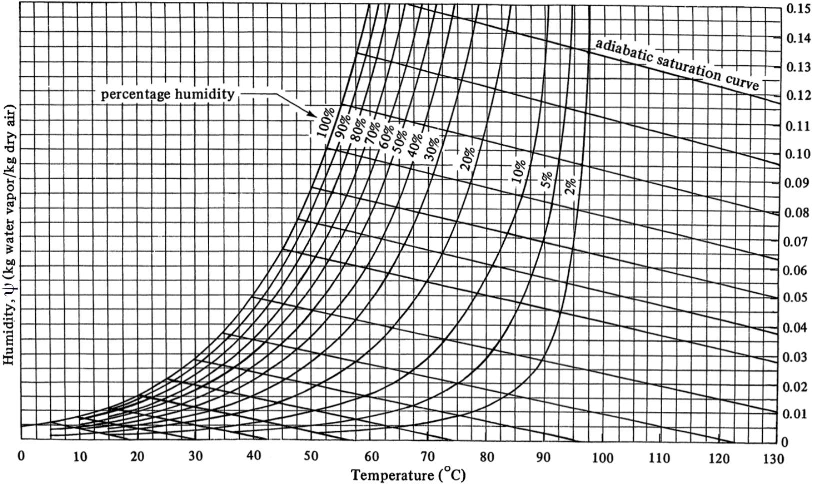
In all cases: $G = 3\,600\,\rho v_{\text{avg}}$ where v and ρ are in SI units and G is in [$\text{kg.hr}^{-1}.\text{m}^{-2}$] already

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}
    - $\mathbf{h = 0.0204G^{0.8}}$ [$\text{W.m}^{-2}.\text{K}^{-1}$] $\longleftarrow$ **G has non-SI units here!**

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}
    - $\mathbf{h = 1.17G^{0.37}}$ [$\text{W.m}^{-2}.\text{K}^{-1}$]

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

Why these equations makes sense



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

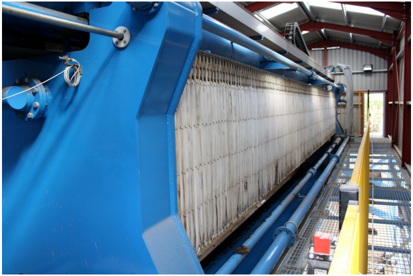
$$h = a(G)^b = a(\rho v)^b$$

Wet basis and dry basis

1. Wet basis
   - For example, if we have 200 kg of moist solids, that contains 30% moisture (wet basis)
   - 30% of that is moisture $= 0.3 \times 200 = 60$ kg of water
   - 70% of that is solid $= 0.7 \times 200 = 140$ kg of dry solid

2. Dry basis
   - For example, if we have 200 kg of moist solids, that contains 30% moisture (dry basis)
   - Consider a 100 kg amount of moist solids, and ratio against it
   - $\dfrac{30 \text{ kg water}}{30 \text{ kg water} + 100 \text{ kg solid}} \times 200$ kg moist solids
   - Moisture amount $= \dfrac{30}{130} \times 200 = 46.2$ kg water
   - Solids amount $= \dfrac{100}{130} \times 200 = 153.8$ kg dry solid

Filter cake drying example



[Flickr, CC BY 2.0]

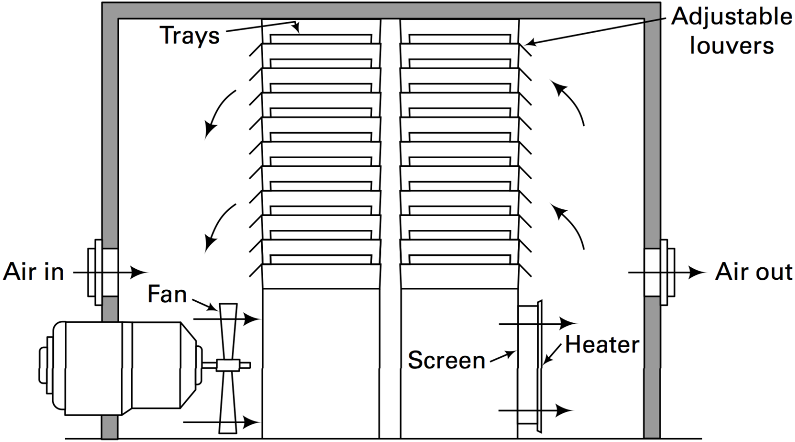
[Flickr, CC BY 2.0]

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 15% (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.



[Seader, Henley and Roper, p 728]

Space for calculations

Filter cake drying example

1. What is the humidity of the incoming air stream?
2. What is the wet-bulb temperature of this air stream?
3. What is the humid volume of the drying air stream?
4. Estimate the heat transfer coefficient.
   - $G = 3\,600\,\rho v_{\text{avg}} = 3\,600(1.048)^{-1} \times 4 =$
   - $h = 0.0204(13\,740)^{0.8} =$
5. Substitute into the constant-drying rate expression to find:
   - drying time $= \dfrac{(\Delta M_{\text{water}})(\Delta H_{\text{vap}})}{hA(T_{\text{db}} - T_{\text{wb}})} = \dfrac{(19.5)(2401 \times 1000)}{(41.7)(2)(75 - 41.3)} =$
   - Water initially $= 30$ kg; dry basis $= 0.15 = \dfrac{30 - \Delta M_{\text{water}}}{70\,\text{kg dry solids}}$
   - So $\Delta M_{\text{water}} = 19.5\,\text{kg}$
   - We need the ΔH_{vap} at T_{wb} (why?) [2401 kJ/kg]
     - 2501 kJ/kg at 0°C
     - 2260 kJ/kg at 100°C

Example: extended

What if we used a perpendicular (impinged) flow of air at 4 m/s?

h will change! Use an alternative correlation, but check it's validity first.

$$\begin{aligned} h &= 1.17G^{0.37} \\ h &= 1.17(13\,740)^{0.37} = 39.74\ \mathrm{W.m^{-2}.K^{-1}} \end{aligned}$$

So slightly longer drying time required. No real benefit of perpendicular flow.

What if we created spherical pellets of particles first?

- if $N_{Re} < 350$, then $h = 0.214\dfrac{G^{0.49}}{d_p^{0.51}}$
- if $N_{Re} \geq 350$, then $h = 0.151\dfrac{G^{0.59}}{d_p^{0.41}}$
- d_p is equivalent spherical particle diameter in m
- $N_{Re} = \dfrac{d_p G}{\mu}$, but G is in SI units now, and
- $\mu \approx 2 \times 10^{-5}\,\mathrm{kg.m^{-1}.s^{-1}}$