Separation Processes:
Drying
ChE 4M3

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- **any suggestions to improve the notes**

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If reporting errors/updates, please quote the current revision number: 288

References used (in alphabetical order)

- Geankoplis, “Transport Processes and Separation Process Principles”, 4th edition, chapter 9.
- Perry’s Chemical Engineers’ Handbook, 8th edition, 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, Henley and Roper, “Separation Process Principles”, 3rd edition, chapter 18.
- Uhlmann’s Encyclopedia, “Drying”, DOI:10.1002/14356007.b02_04.pub2

Background

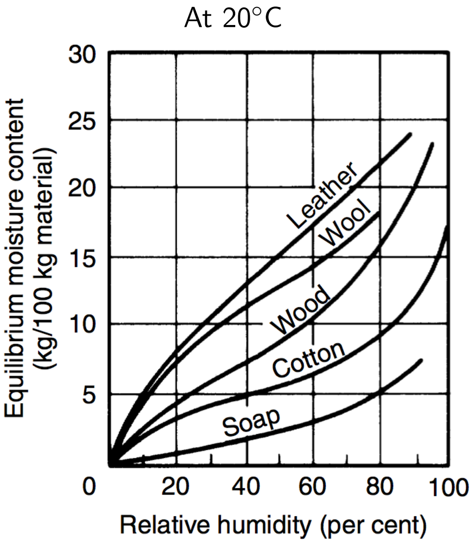
We consider **drying of solid products** here.

- Remove liquid phase from solid phase by an ESA = thermal energy
- It is the final separating step in many processes, especially after a filtration step
  - 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

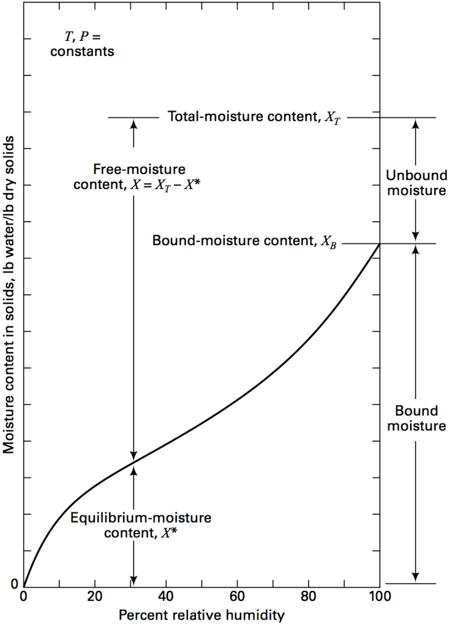
The nature of water in solid material



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

[Richardson and Harker, p 902]

The nature of water in solid material



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

[Seader, Henley and Roper, p 749]

Drying: the heat and mass transfer view points

Both heat and mass transfer occur simultaneously

Mass transfer

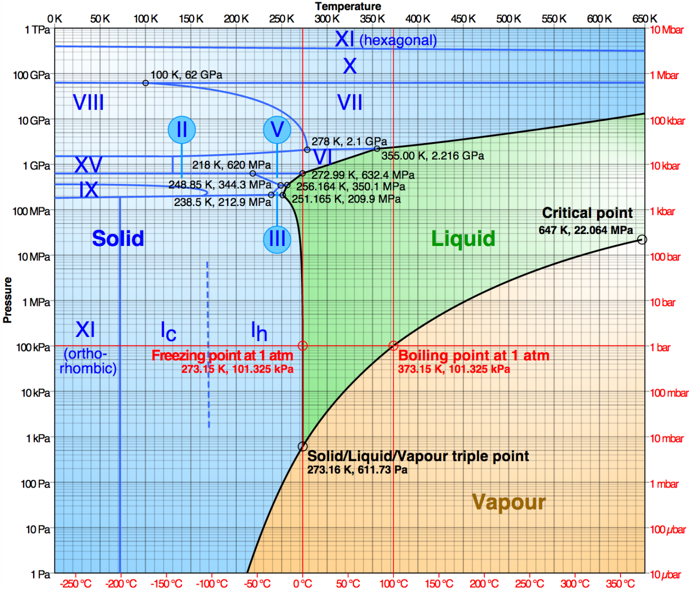
- Bring liquid from interior of product to surface
- Vapourization of liquid at/near the surface
- Transport of vapour into the bulk gas phase

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 adiabatically provided by the air stream. Air is cooled as a result of this evaporation
- The ΔH_{vap} is 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]

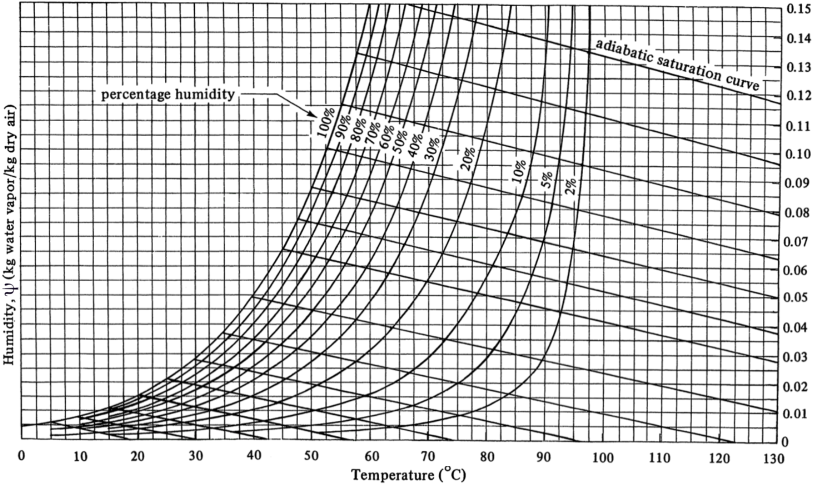
Terminology

- 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]
  - ethanol's vapour pressure at room temperature: $\approx$ 6000 Pa
  - water's vapour pressure at room temperature: $\approx$ 2300 Pa

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



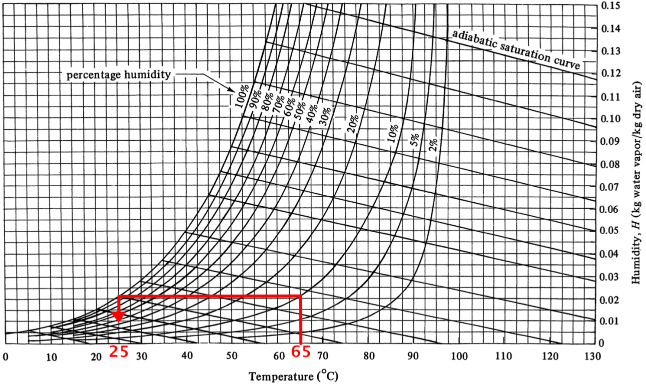
[Geankoplis, p568; multiple internet sources have this chart digitized]

Terminology

- Dry bulb temperature: or just T_{db} = "*temperature*"
  - 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:
  - $\psi_S =$ 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
  - $P =$ total pressure $= 101.325$ kPa in this psychrometric chart

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

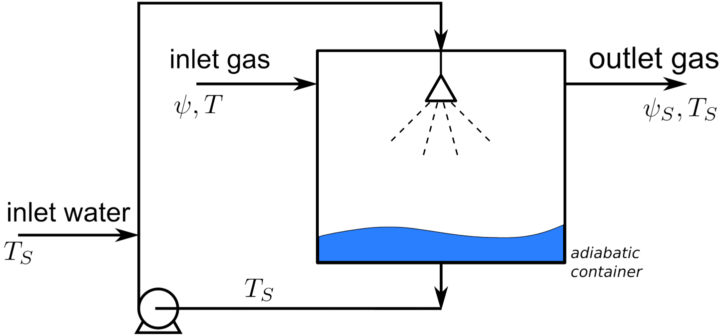
- Humid heat: amount of energy to raise 1kg of air and the water vapour it contains by 1°C

$$c_S = 1.005 + 1.88\psi$$

  - 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 $\left[\dfrac{\text{kg water vapour}}{\text{kg dry air}}\right]$

Terminology: adiabatic saturation

Consider a stream of air at temperature T and humidity ψ. It adiabatically contacts fine water droplets long enough to reach equilibrium (i.e. saturation).



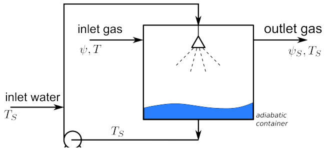
We expect outlet gas temperature $= T_S < T$ and outlet humidity of $\psi_S > \psi$.

Energy to evaporate liquid water into the outlet air stream comes from the air.

Terminology: adiabatic saturation

Quantify it: do an enthalpy balance at $T_{\text{ref}} = T_S$

i.e. we can disregard water; and at T_s water is in liquid phase



Enthalpy of vapour phase entering:

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

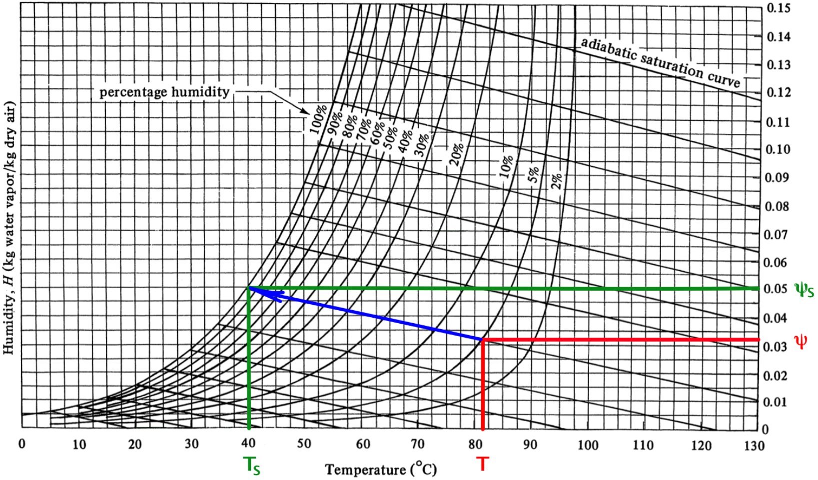
Enthalpy of vapour phase leaving:

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

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

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

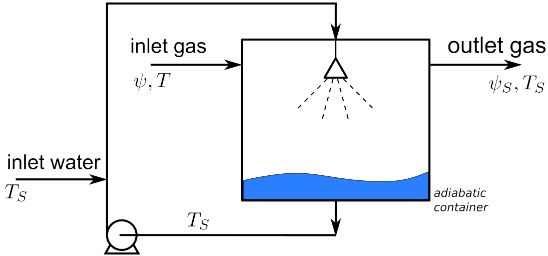
Adiabatic saturation temperature



Exercise

An air stream at 70°C and carrying 55 g 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.

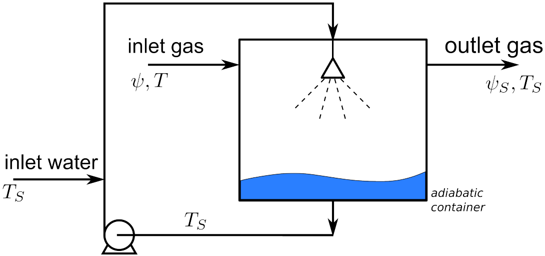
1. What is the percentage humidity of the incoming air stream?
2. What is the percentage humidity of the air stream leaving?
3. What is the humidity [mass/mass] of the air stream leaving?
4. What is the temperature of the air stream leaving?
5. If the contacting takes place in a unit shown below, what is the mass of inlet make-up water required at steady-state operation?



Exercise

An air stream at 70°C and carrying 55 g 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.

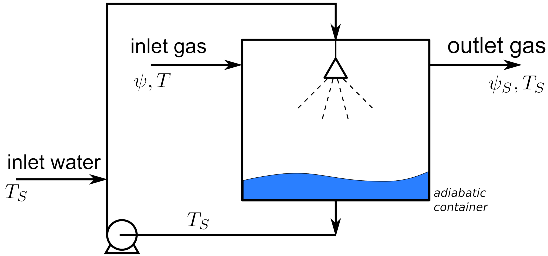
1. What is the percentage humidity of the incoming air stream? [20%]
2. What is the percentage humidity of the air stream leaving?
3. What is the humidity [mass/mass] of the air stream leaving?
4. What is the temperature of the air stream leaving?
5. If the contacting takes place in a unit shown below, what is the mass of inlet make-up water required at steady-state operation?



Exercise

An air stream at 70°C and carrying 55 g 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.

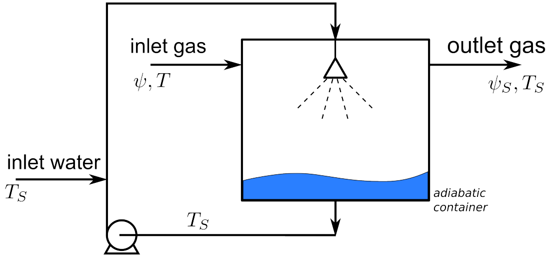
1. What is the percentage humidity of the incoming air stream? [20%]
2. What is the percentage humidity of the air stream leaving? [100%]
3. What is the humidity [mass/mass] of the air stream leaving?
4. What is the temperature of the air stream leaving?
5. If the contacting takes place in a unit shown below, what is the mass of inlet make-up water required at steady-state operation?



Exercise

An air stream at 70°C and carrying 55 g 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.

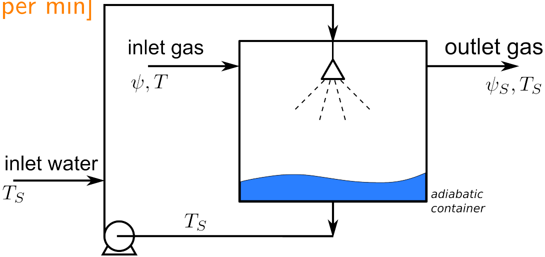
1. What is the percentage humidity of the incoming air stream? [20%]
2. What is the percentage humidity of the air stream leaving? [100%]
3. What is the humidity [mass/mass] of the air stream leaving? [66g/kg]
4. What is the temperature of the air stream leaving?
5. If the contacting takes place in a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



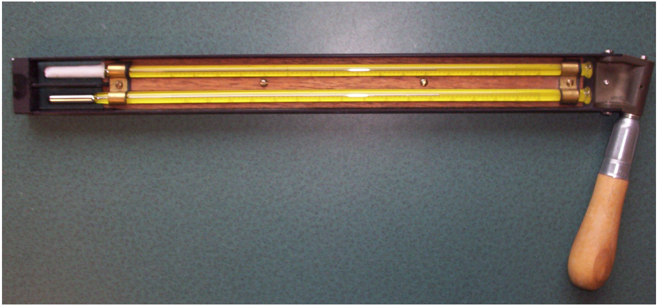
Exercise

An air stream at 70°C and carrying 55 g 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]

- 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 same slopes - *for water only!*)
- the *temperature* we consider evaporation to be occurring at, right 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:

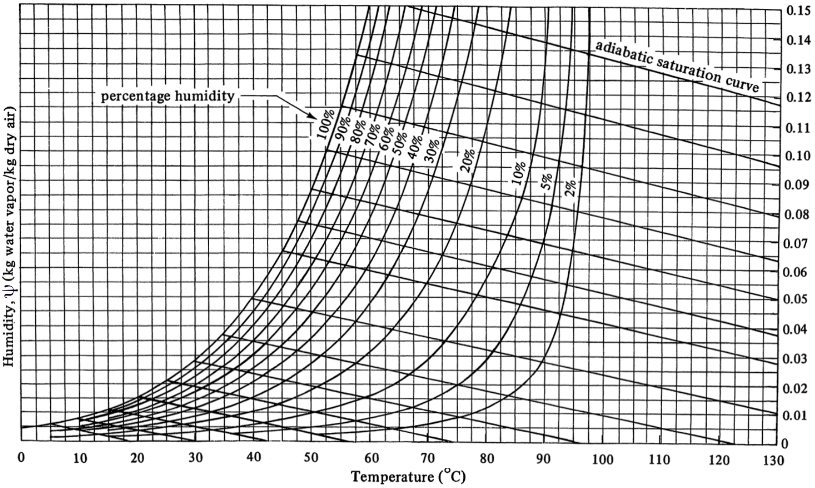
$$v_H = \left[2.83 \times 10^{-3} + 4.56 \times 10^{-3}\psi\right] T_{\text{db}} \qquad \left[\frac{\text{m}^3}{\text{kg moist air}}\right]$$

- 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

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

Psychrometric chart



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

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

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 [55°C]
- percentage humidity [26%]
- dew point temperature [$\approx$ 31°C]
- humid heat $\left[c_S = 1.061 \frac{\text{kJ}}{\text{(kg dry air)(K)}}\right]$
- humid volume [$T = 328\text{K}$; $v_H = 0.973\text{m}^3/\text{(kg moist air)}$]
- wet-bulb temperature [$\approx$ 36°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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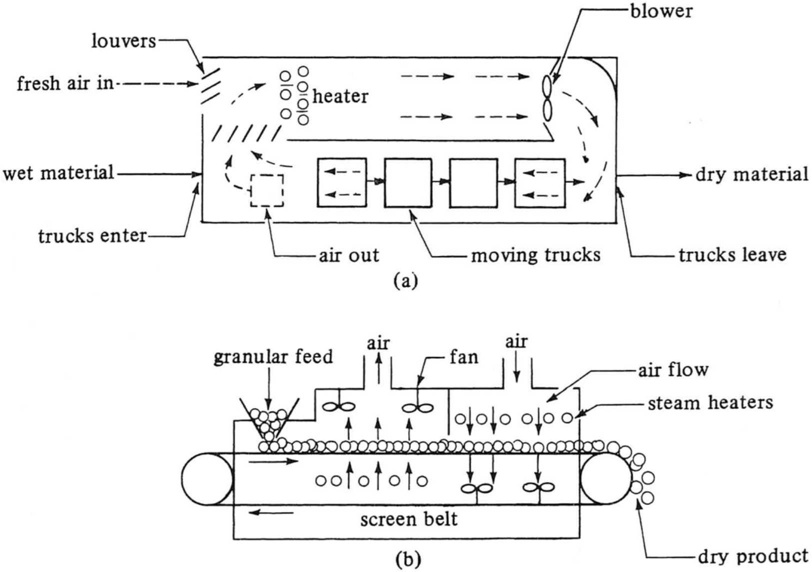
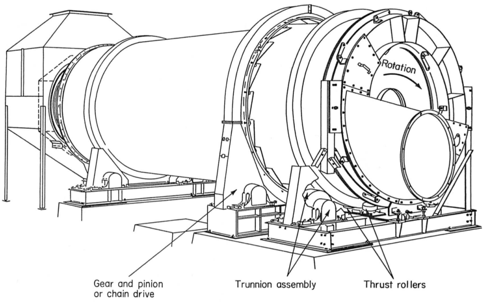
* See Schweitzer; See Perry's; See Seader, Henley and Roper

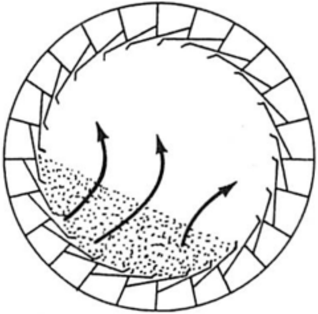
Some equipment examples: Continuous tunnel dryer



[Geankoplis, p 561]

Some equipment examples: Rotating dryer

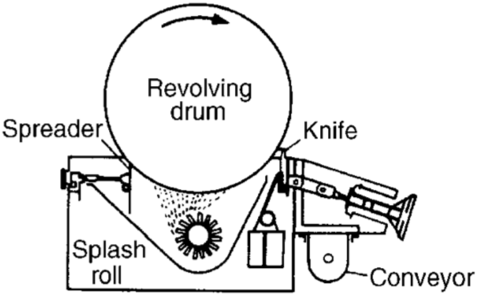




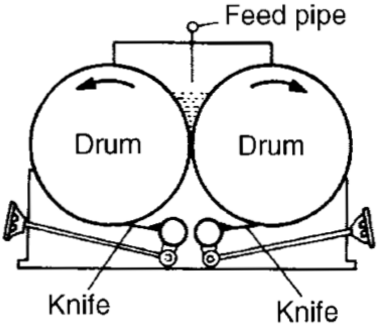
[Schweitzer, p 4-161 and 4-162]

- 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
- Link to a video

Some equipment examples: Drum dryers



Splash feed

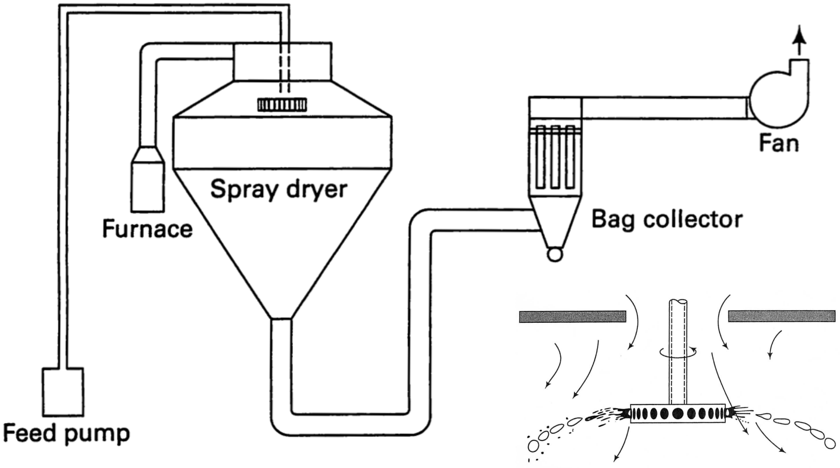


Double drum, top feed

[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

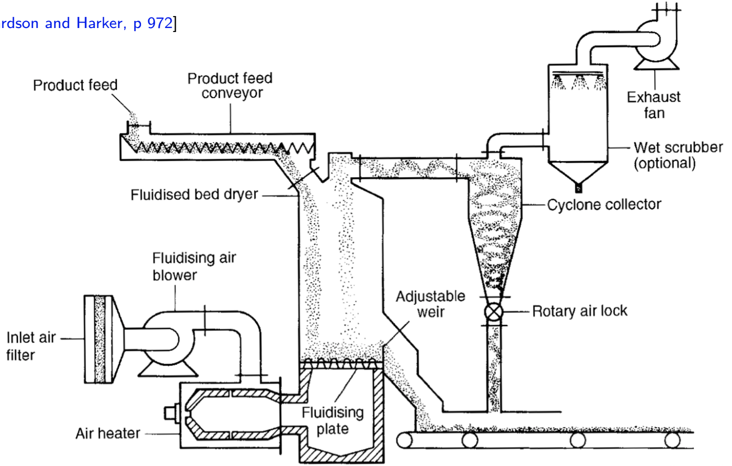


[Seader, Henley and Roper, p 737]

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

Some equipment examples: Fluidized bed dryer

[Richardson and Harker, p 972]

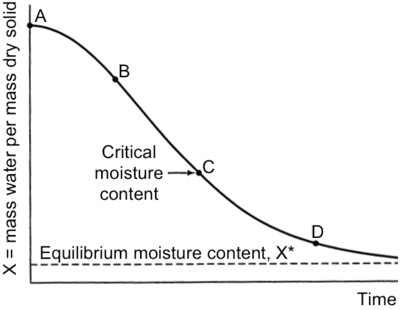


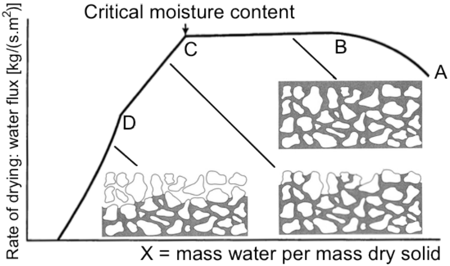
- upward flowing air stream (elutriation)
- turbulent mixing: good heat and mass transfer
- uniform solid temperature
- solids are gently treated
- solids are retrieved via gravity and cyclones
- fluidizing air scrubbed before vented

Drying profiles

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

[Seader, Henley and Roper, 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.
- Assumes: all the heat provided is only used to evaporate liquid

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

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!

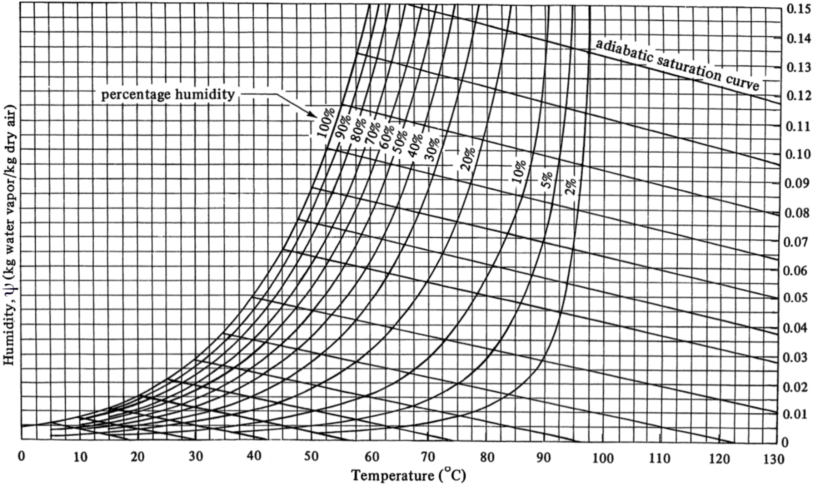
In all cases: $G = 3\,600\,\rho v_{\text{avg}}$ where v and ρ are in SI units and G is in $[\text{kg.hr}^{-1}.\text{m}^{-2}]$ already

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



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

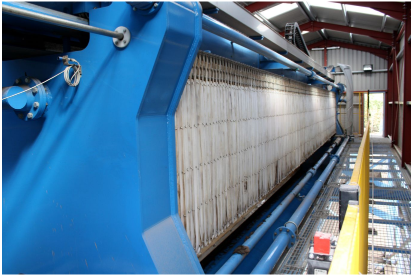
$$h = a(G)^b = a(\rho v)^b$$

Wet basis and dry basis

1. **Wet basis = (mass of water)/(mass of wet solids)**
   - For example, if we have 200 kg of wet 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 = (mass of water)/(mass of dry solids)**
   - For example, if we have 200 kg of wet solids, that contains 30% moisture (dry basis)
   - Consider a 100 kg amount of ~~moist~~ dry solids, and ratio against it
   - $\dfrac{30 \text{ kg water}}{30 \text{ kg water} + 100 \text{ kg solid}} \times 200$ kg wet solids
   - Moisture amount $= \dfrac{30}{130} \times 200 = 0.231 \times 200 = 46.2$ kg water
   - Solids amount $= \dfrac{100}{130} \times 200 = 153.8$ kg dry solid

Filter cake drying example



[Flickr, CC BY 2.0]

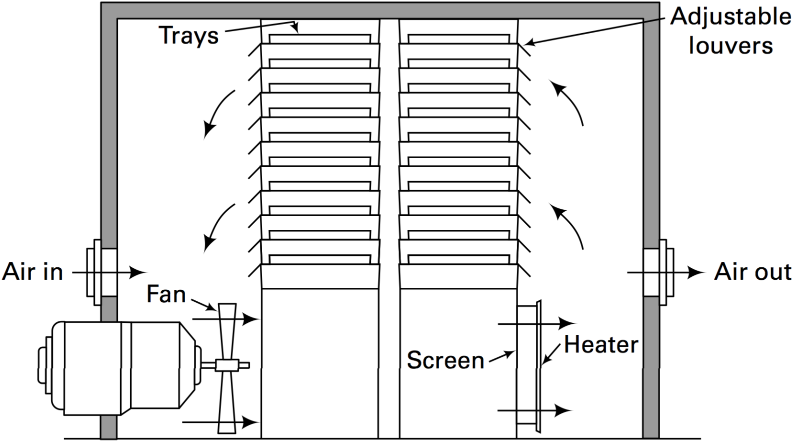
[Flickr, CC BY 2.0]

Consider 100kg of cake, discharged at 30% moisture (wet basis). Air to dry the cake at 75°C is used, 10% 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]

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?)
     - 2501 kJ/kg at 0°C
     - 2260 kJ/kg at 100°C

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, $v_H = 1.048\text{m}^3.\text{kg}^{-1}$]

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 $= \dfrac{(\Delta M_{\text{water}})(\Delta H_{\text{vap}})}{hA(T_{\text{db}} - T_{\text{wb}})} = \dfrac{(19.5)(2401 \times 1000)}{(41.7)(2)(75 - 41.3)} =$

     drying time = **4.6 hrs**

   - 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 $\text{kJ.kg}^{-1}.\text{K}^{-1}$]
     - 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.

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

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
- $\mu \approx 2 \times 10^{-5}\,\text{kg.m}^{-1}.\text{s}^{-1}$