Separation Processes

ChE 4M3

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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: 143

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.

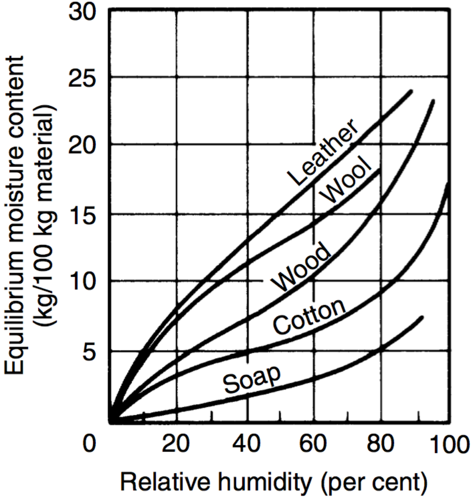
- Remove liquid phase from solid phase by an ESA = thermal energy
- It is the final separating step in many processes
  - pharmaceuticals
  - foods
  - crops, grains and cereal products
  - lumber, pulp and paper products
  - catalysts, fine chemicals
  - detergents

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

At 20°C



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

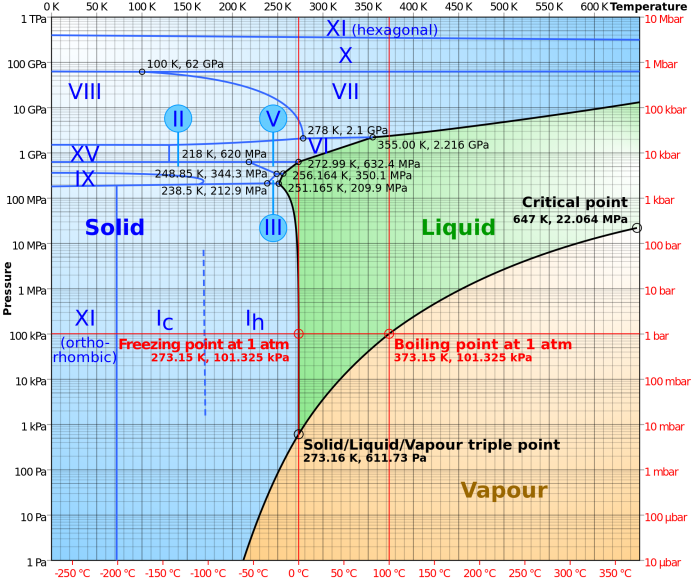
- Bring liquid from interior of product to surface
- Vapourization of liquid at/near the surface
- Transport of vapour into the bulk gas phase

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

Terminology



[Wikipedia File:Phase_diagram_of_water.svg]

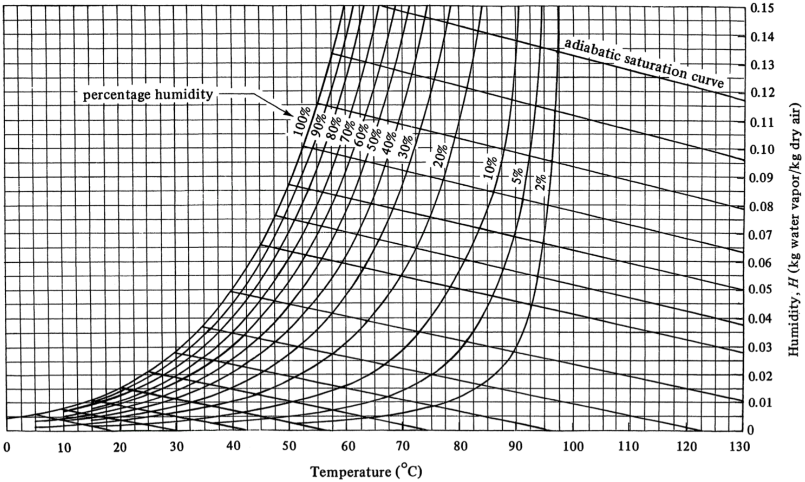
Terminology

- 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



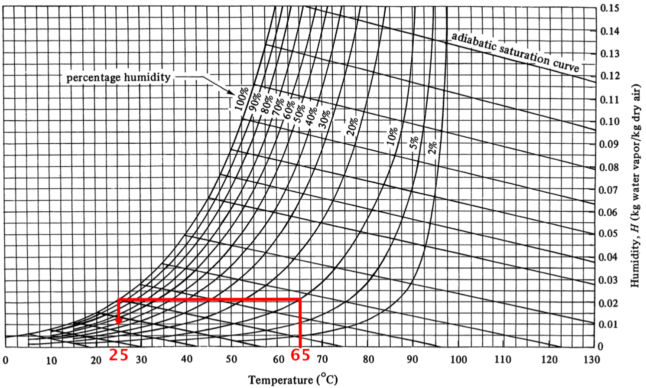
[Geankoplis, p568; multiple internet sources have this chart digitized]

Terminology

- Dry bulb temperature: or just T = "*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:
  - $\psi_S =$ 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

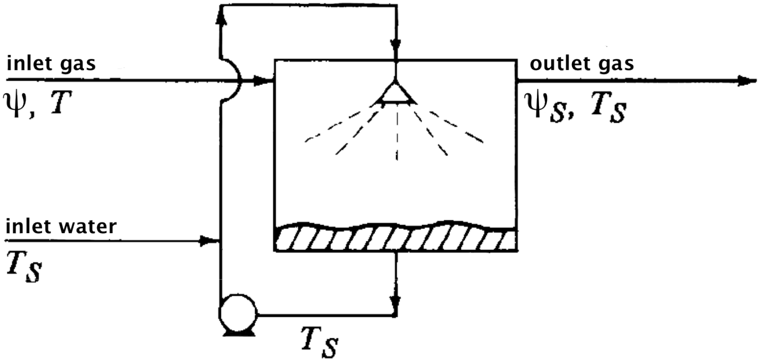
- Humid heat: amount of energy to raise 1kg of air and the water vapour it contains by 1°C

$$c_S = 1.005 + 1.88\psi$$

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

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.

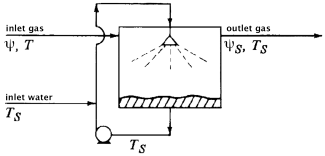


We expect outlet gas: $T_S < T$ and $\psi_S > \psi$

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.

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.

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 on the previous slide, what is the mass of inlet make-up water required at steady-state operation?

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