Mass Transfer and Separations Processes I

Revision Lecture

DEN5406

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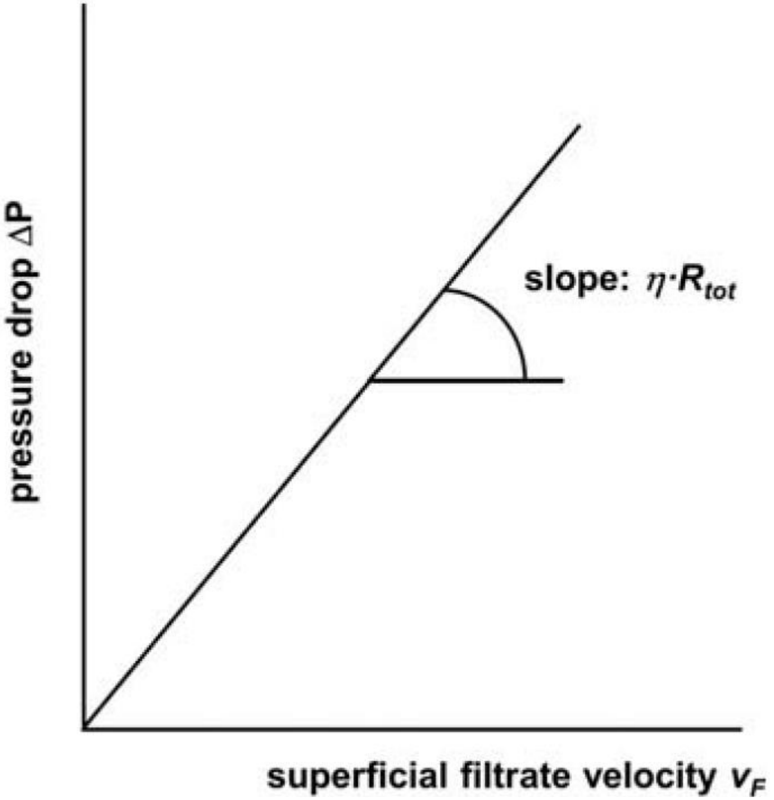
Outline

1. Cooking – intro – learn concepts – but also solve them in Excel
2. Purifying dirty water – to drink
    a. Sterilizing methods – kill or remove pathogens - membrane
    b. Purifying from chemicals – distillation – in space
    c. Freezing for purification
    d. Separating Azeotropes
    e. Desalination by ion exchange and reverse osmosis
3. Purifying dirty oil - > so it can be used as fuel, or not spoil
    a. Mechanical separation – filtration
    b. Mechanical separation – centrifugation
4. Extraction from Solids
    a. Espresso from ground beans
    b. Extracting oil from pressed beans and olives
    c. Leaching metals from ores
5. Drying solids – preserving foods
    a. Getting rid of water or stripping the water

Filtration – Quantitation



$$v_F = \frac{\Delta P}{\eta\,(R_M + R_C)}$$

Resistance due to filter medium
And to cake (R_M and R_C)

$$v_F = \frac{1}{A}\frac{dV}{dt}$$

$$\Delta P = \Delta P_C + \Delta P_M = \eta\,\frac{R_C + R_M}{A}\,\frac{dV}{dt}$$

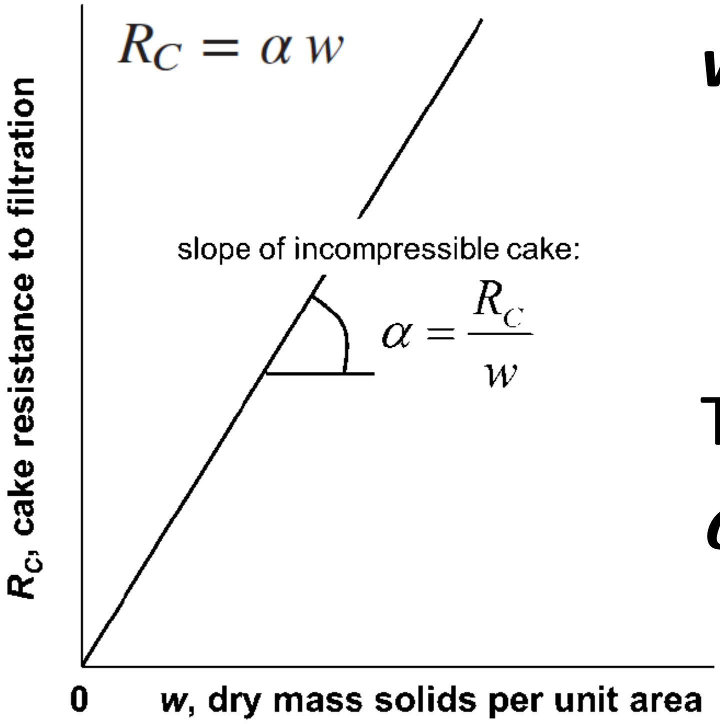
Darcy's Law

De Haan & Bosch, Industrial
Separation Processes, 2013, Ch 10.

Filtration – Incompressible Cake

Incompressible cake causes:

a *linear* increase in resistance R_C with *cake height*



w is mass dry solids per filter area A

$$w = \frac{c\,V}{A}$$

[kg/m2] where c is kg solids per volume V of suspension

The proportionality slope R_C / w is

α - the **specific cake resistance** **[m/kg]**

Darcy's Law with specific resistance:

$$\eta\, \frac{R_C + R_M}{A}\, \frac{dV}{dt} \Rightarrow \Delta P = \frac{\eta\, c\, \alpha}{A^2}\, V\, \frac{dV}{dt} + \frac{\eta\, R_M}{A}\, \frac{dV}{dt}$$

Simple vs. Flash Distillation

Same, yet

Batch vs. Continuous

$$y = \frac{\alpha x}{1 + (\alpha - 1)\, x} \quad \text{with} \quad \alpha = \frac{K_A}{K_B}$$

Single stage separation efficiency.
Relative volatility *α* is the equilibr.
VL- constant, also referred to as *K*

continuous feed is partially
vaporized to give a vapor richer
in the more volatile components.
limited degree of separation
Uses:e.g. seawater desalination,
Where bp differences are high

Above is derived from Two Mass Balances –
One for whole liquid, one for a component in the liquid

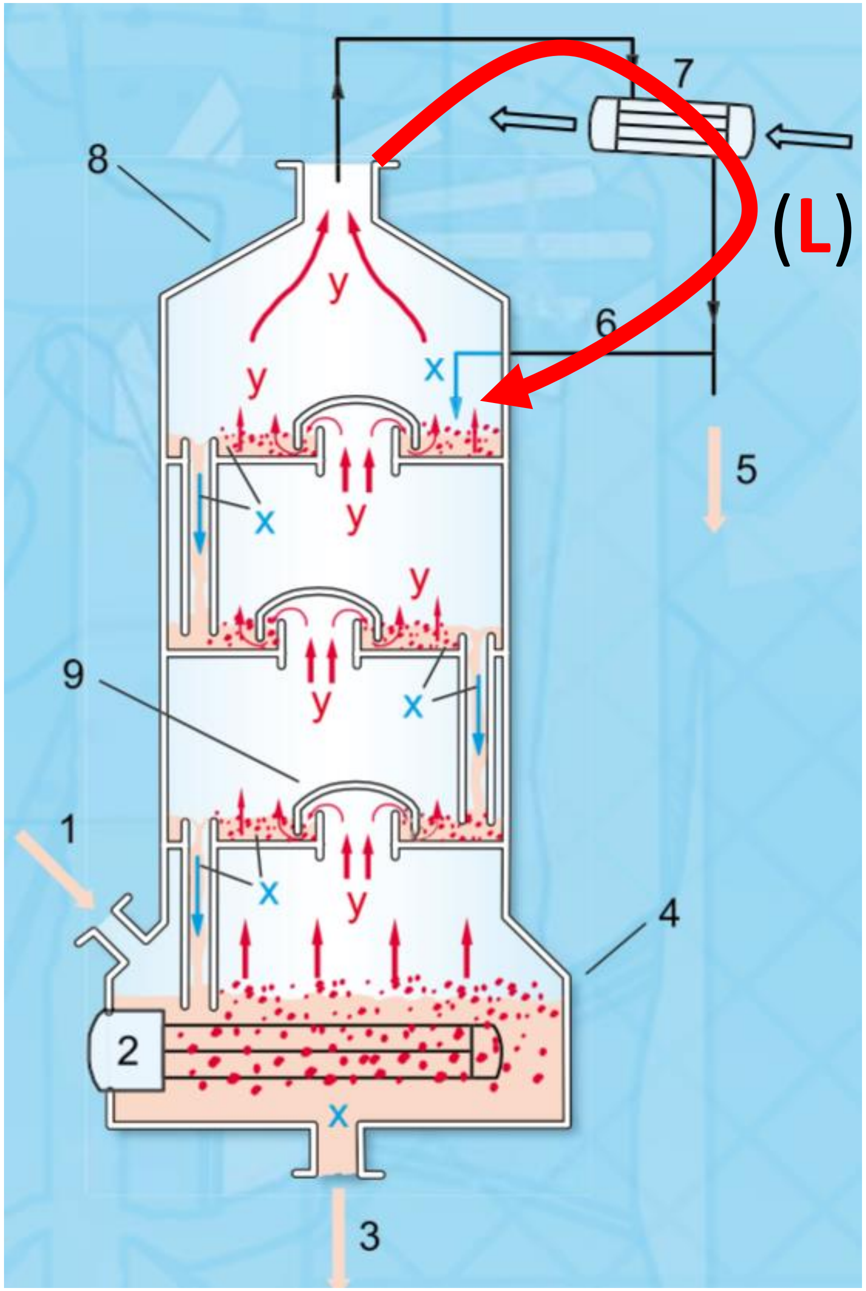
$$F = V + L \quad \text{and} \quad Fz = Vy + Lx$$

Here F is the total fluid and
V, L – vapor and liquid separated

z, y, x, and the mole fractions of
a component in fluid, vapor, liquid

Multi-Stage and Column Distillation

with Rectification



Top vapor = product

Part condensed, fed back

Words for vocabulary:
distillation column, Reflux, rectification, reflux ratio, reboiler, Operating pressure

The **Reflux ratio** **R = L/D** is the ratio of reflux flow (**L**) to distillate flow (**D**)

(**L** Being returned back to the column for re-distilling)

Two-Phase Equilibria

In Distillation

$$K_i \equiv \frac{y_i}{x_i}$$

$$\alpha_{ij} = \frac{K_i}{K_j} :$$

distribution coefficient Ki between phases x,y of component i

the **relative volatility** of ***i*** Determines the selectivity of Separation vs a reference ***j*** is

How do we measure relative volatility?

$$p_i = y_i P_{tot}$$

Dalton's law relates concentration of components in an ideal gas or to partial pressures in the vapor mixture

$$p_i = x_i P_i^0$$

Raoult's law gives partial pressure in the vapor (*pi*) from concentr. in the liquid (*xi*) mixture

Combination gives:

$$y_i P_{tot} = x_i P_i^0 \qquad K_i = \frac{y_i}{x_i} = \frac{P_i^0}{P_{tot}} \quad \text{and} \quad \alpha_{ij} = \frac{K_i}{K_j} = \frac{P_i^0}{P_j^0}$$

Operating condition: T and L/V Graphical Determination – Mole Fractions

When we specify T, we can also Decide on q

$\boxed{q = \frac{L}{F}}$ = Fraction of feed remaining liquid

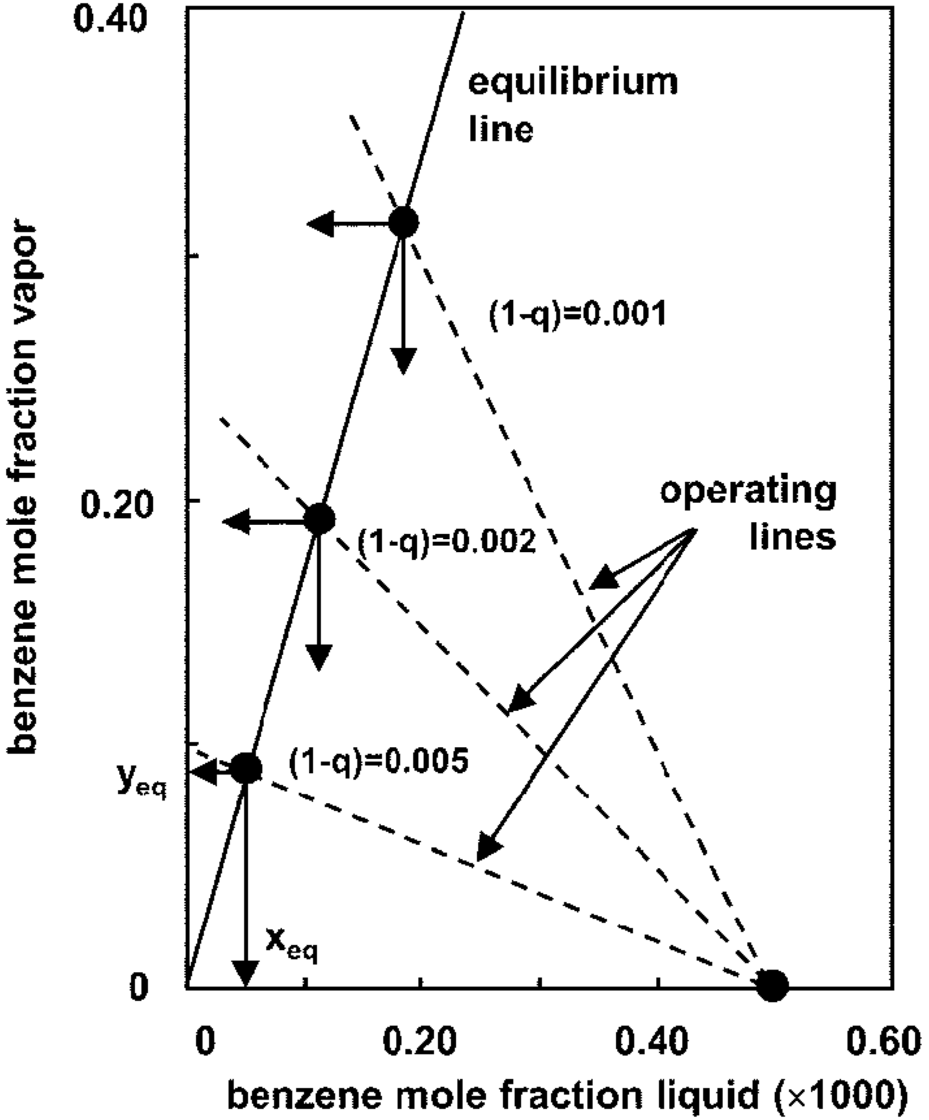
$(1-q) = V / F$ (Fraction vaporized)

The **Operating Line equation** is:

$$y = -\frac{q}{1-q}x + \frac{1}{1-q}z$$

The **Equilibrium line** is:

$$\frac{y}{1-y} = \alpha \cdot \frac{x}{1-x}$$



Operating condition: T and total Pressure P
Graphical Determination – Mole Fractions

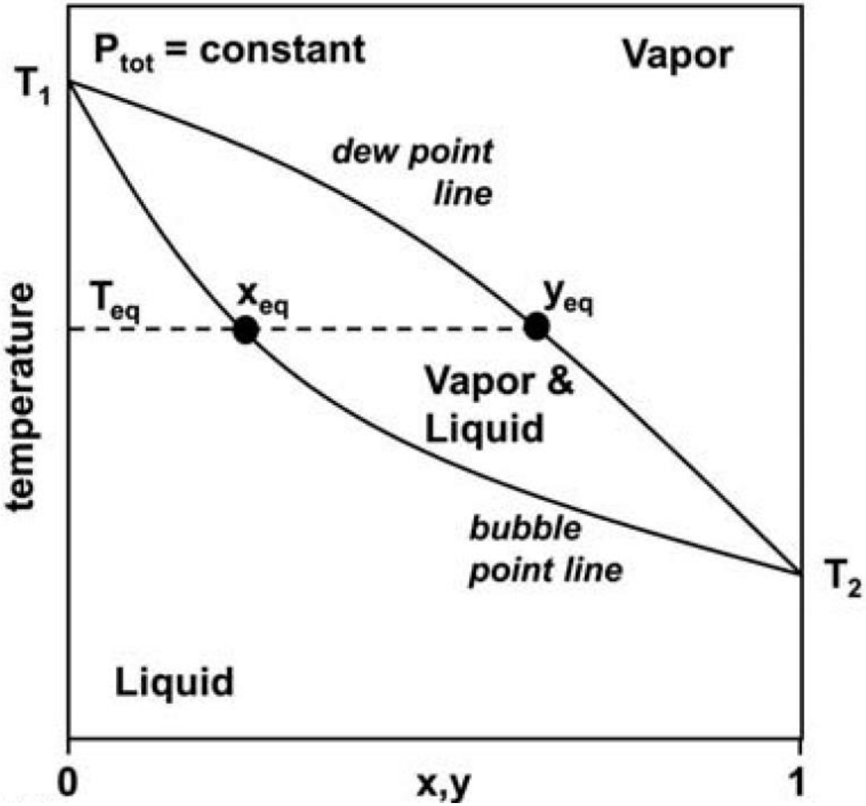
Now we have to find q

$$\boxed{q = \frac{L}{F}}$$ = Fraction of feed remaining liquid

by eliminating x, y from the

Operating Line equation:

$$y = -\frac{q}{1-q}x + \frac{1}{1-q}z$$



And **Equilibrium line**:

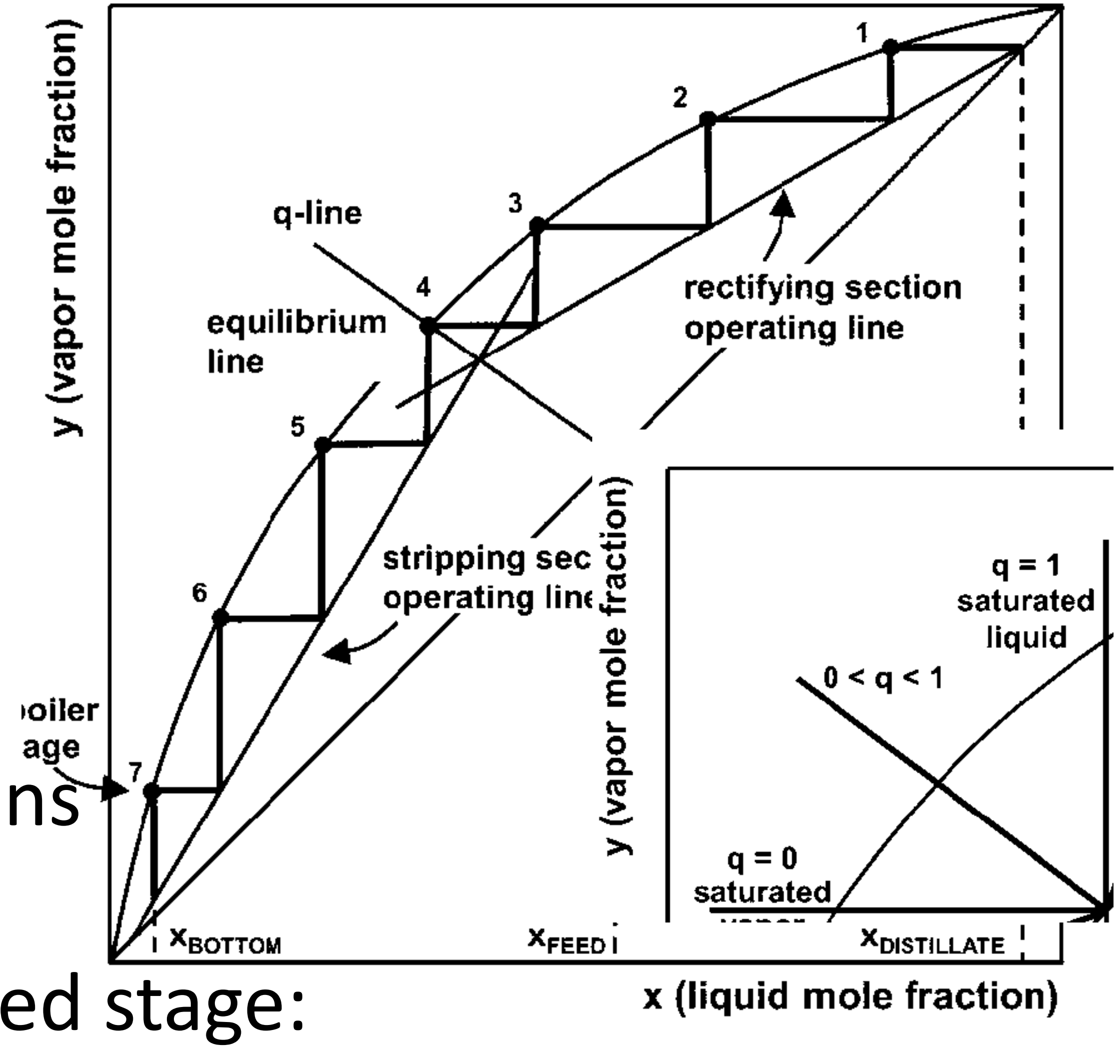
$$\frac{y}{1-y} = \alpha \cdot \frac{x}{1-x}$$

given T, P_{tot} – the K_i are known constants, so

$$q = -z\frac{K_B}{1-K_B} - (1-z)\frac{K_A}{1-K_A} \quad \text{and} \quad x = \frac{1-K_B}{K_A-K_B}$$

McCabe-Thiele Analysis

Graphical Determination of # of equilibrium stages:



First:

Construct a staircase

Between

Operating lines and

Equilibrium curve.

Horizontals – equil.

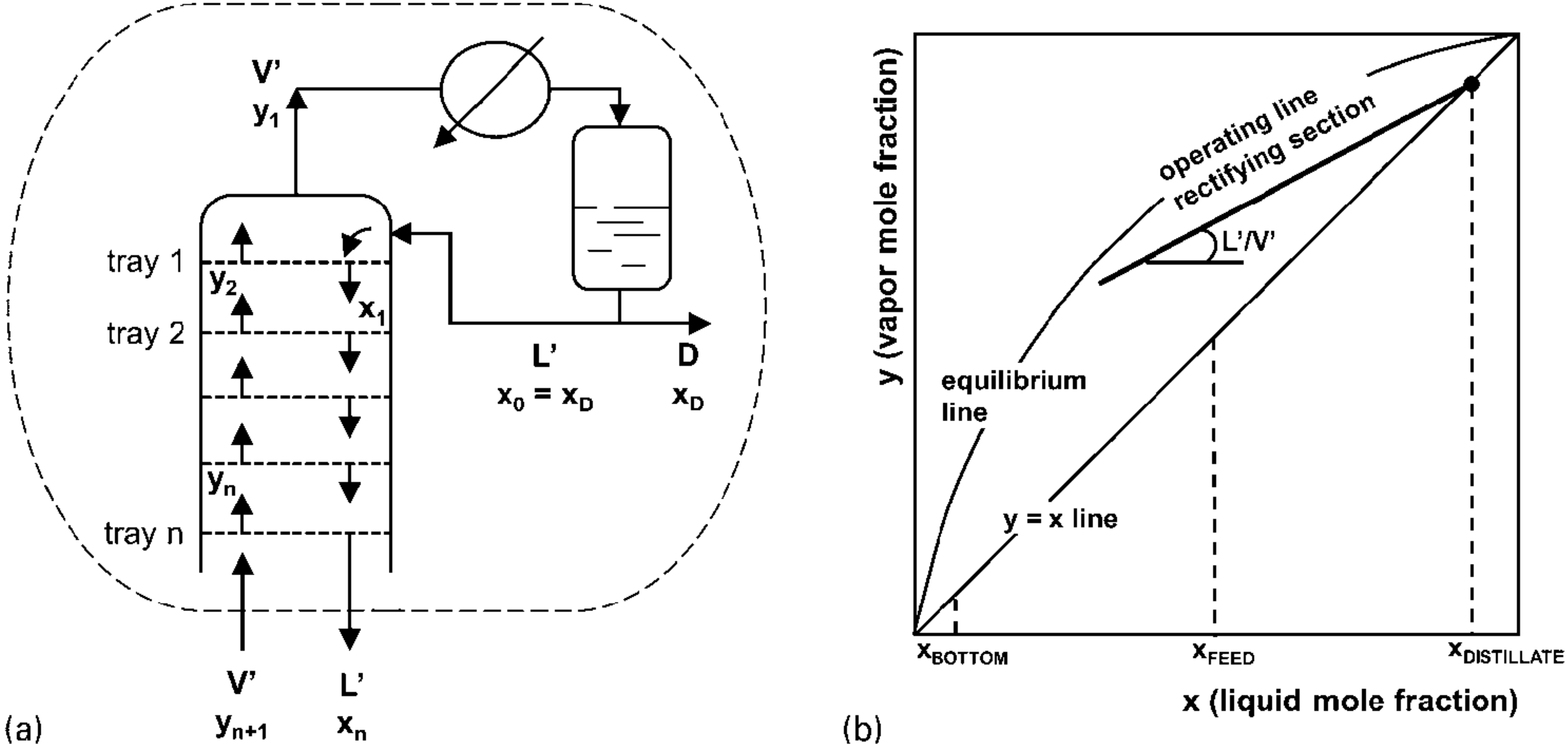
Verticals – compositions

Passing each other

Optimal location of feed stage:

First location after horizontal crosses the q-line.

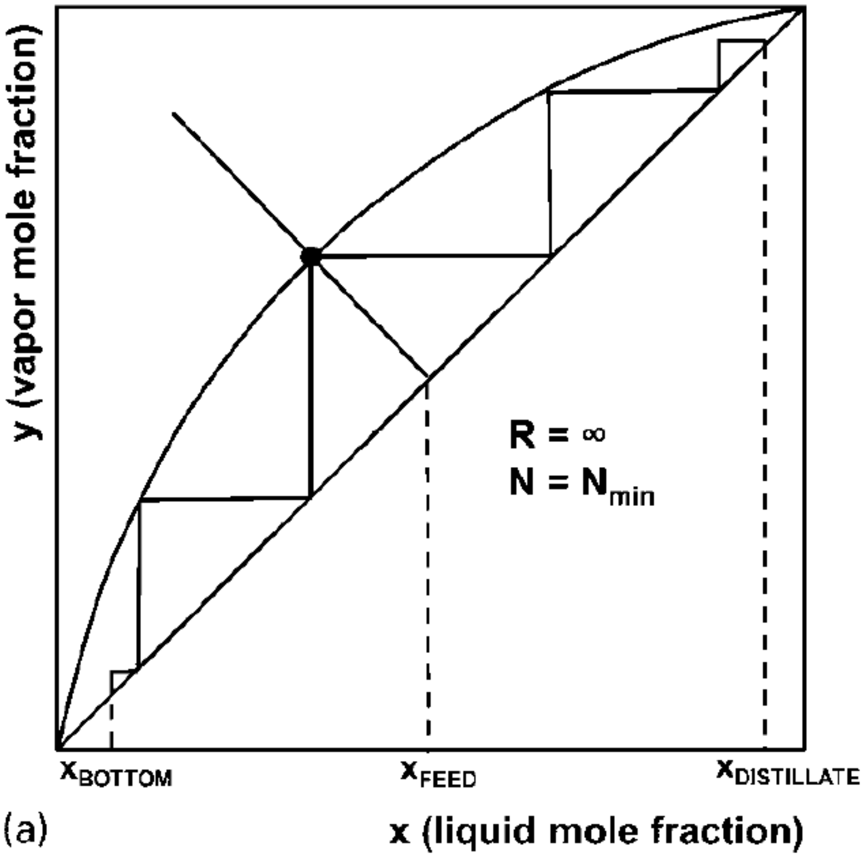
McCabe-Thiele Analysis

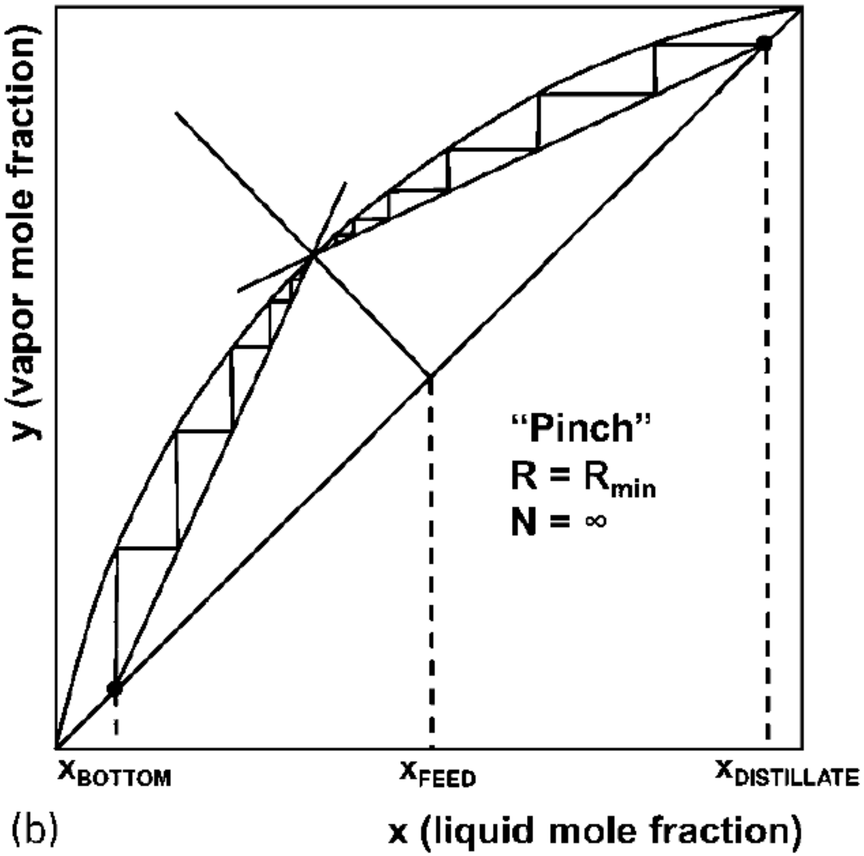


the **operating line** is a straight line in the *y*-*x*-diagram with an intersection at $y = x_D$ on the $y = x$ line, for **specified values of *R* and x_D** (purity of distillate)

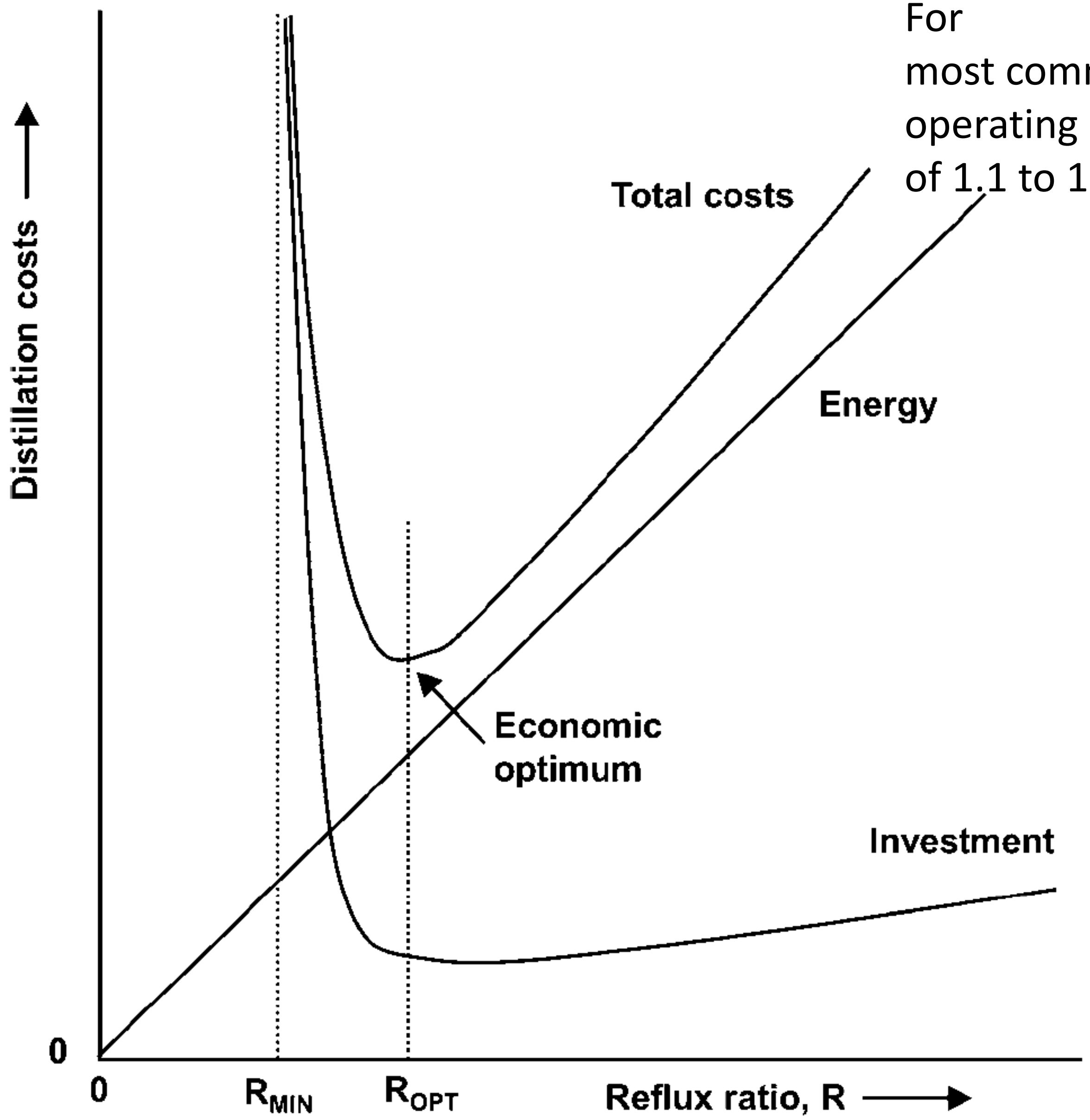
McCabe-Thiele Analysis

Minimum # stages vs. Minimum reflux ratio





McCabe-Thiele Analysis



For
most commercial operations the optimal
operating reflux ratios are in the range
of 1.1 to 1.5 times the minimum reflux ra

Operational cost

McCabe-Thiele Analysis

$$R_{\min} = \left(\frac{L'}{D}\right)_{\min} = \left(\frac{L'}{V' - L'}\right)_{\min} = \frac{\left(\dfrac{L'}{V'}\right)_{\min}}{1 - \left(\dfrac{L'}{V'}\right)_{\min}}$$

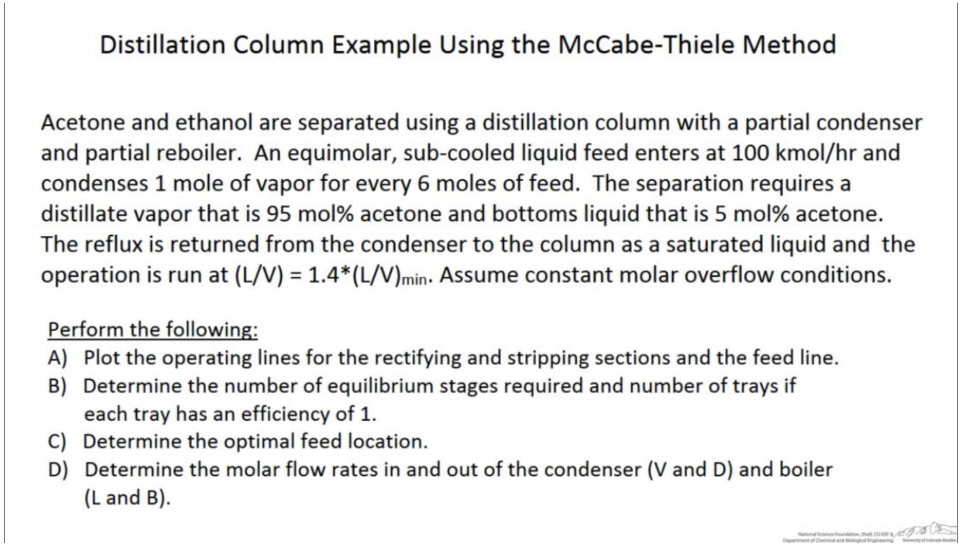
For most commercial operations the optimal operating reflux ratios are in the range of 1.1 to 1.5 times the minimum reflux ratio.

Operational cost

McCabe-Thiele Analysis

One question raised in the revision section – *how does one determine the optimal location of the feed stage*? In the following example, both the distillation and condensation stages are analyzed, and one sees how to find the stage for the initial (specified) composition.

https://youtu.be/0PFVXqLxNF0?t=128 and more detailed examples:

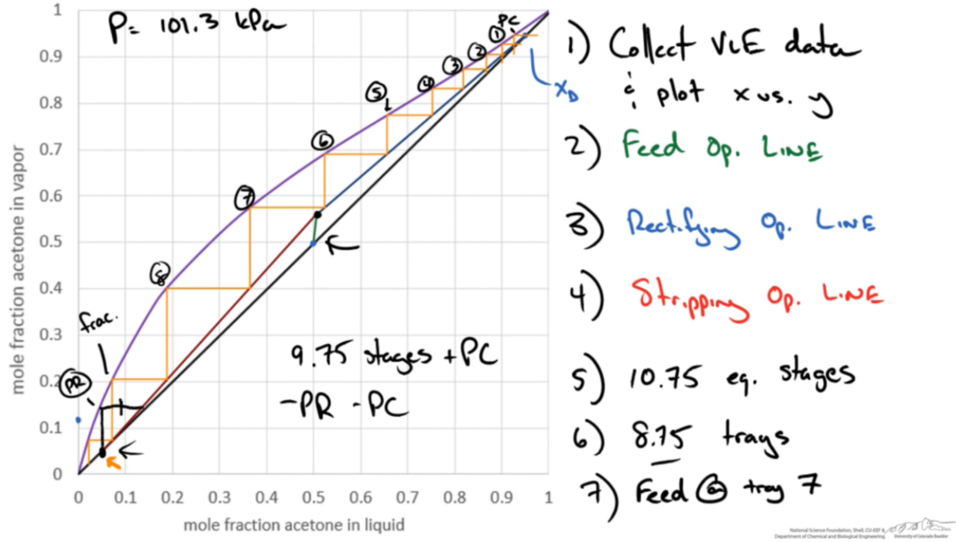


Distillation Column Example Using the McCabe-Thiele Method

Acetone and ethanol are separated using a distillation column with a partial condenser and partial reboiler. An equimolar, sub-cooled liquid feed enters at 100 kmol/hr and condenses 1 mole of vapor for every 6 moles of feed. The separation requires a distillate vapor that is 95 mol% acetone and bottoms liquid that is 5 mol% acetone. The reflux is returned from the condenser to the column as a saturated liquid and the operation is run at (L/V) = 1.4*(L/V)$_{min}$. Assume constant molar overflow conditions.

Perform the following:

A) Plot the operating lines for the rectifying and stripping sections and the feed line.
B) Determine the number of equilibrium stages required and number of trays if each tray has an efficiency of 1.
C) Determine the optimal feed location.
D) Determine the molar flow rates in and out of the condenser (V and D) and boiler (L and B).

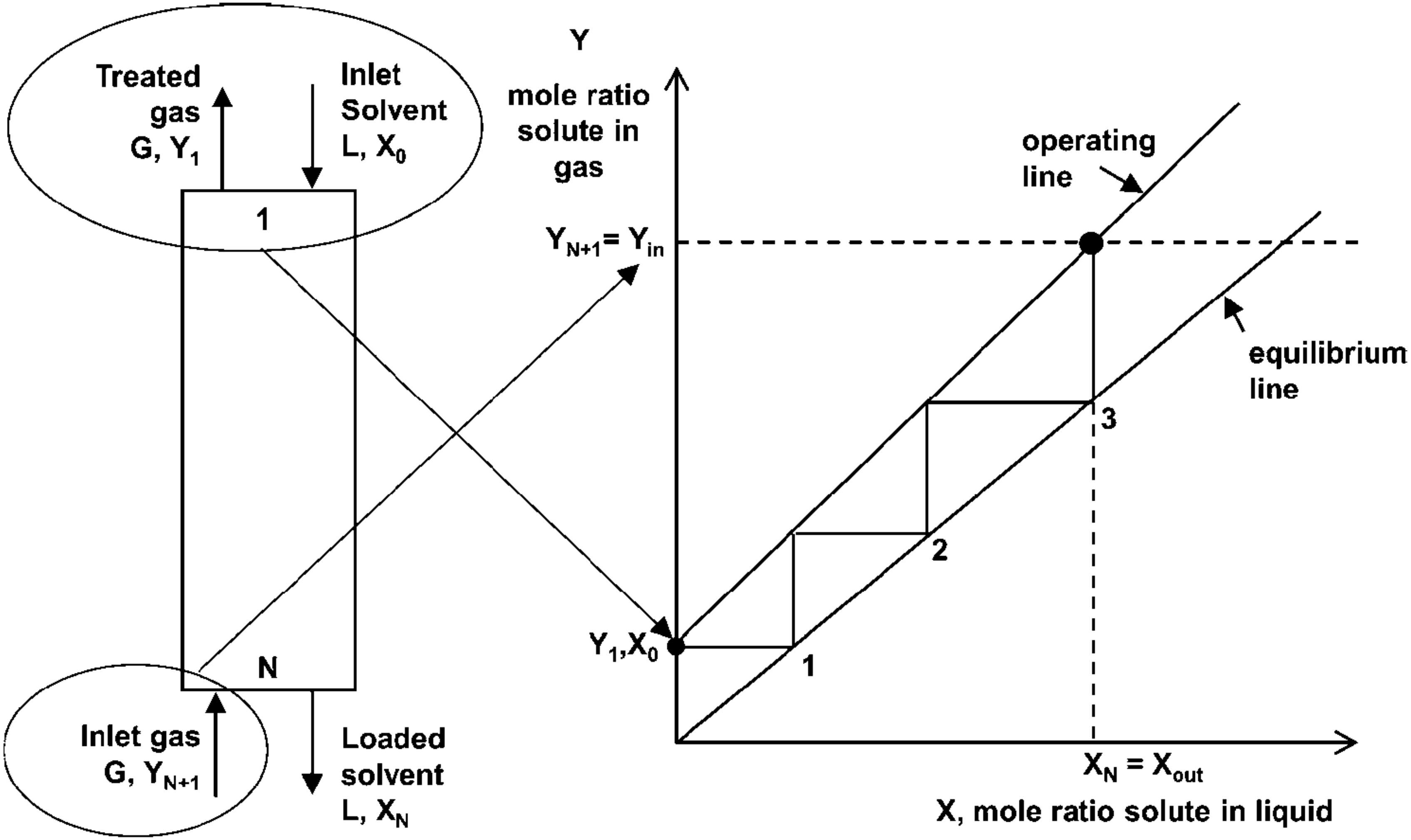


1) Collect VLE data & plot x vs. y
2) Feed Op. Line
3) Rectifying Op. Line
4) Stripping Op. Line
5) 10.75 eq. stages
6) 8.75 trays
7) Feed @ tray 7

https://youtu.be/Cv4KjY2BJTA?t=7

See how after finding the two operation lines One finds the feed location is in stage 7.
https://youtu.be/eIJk5uXmBRc?t=190

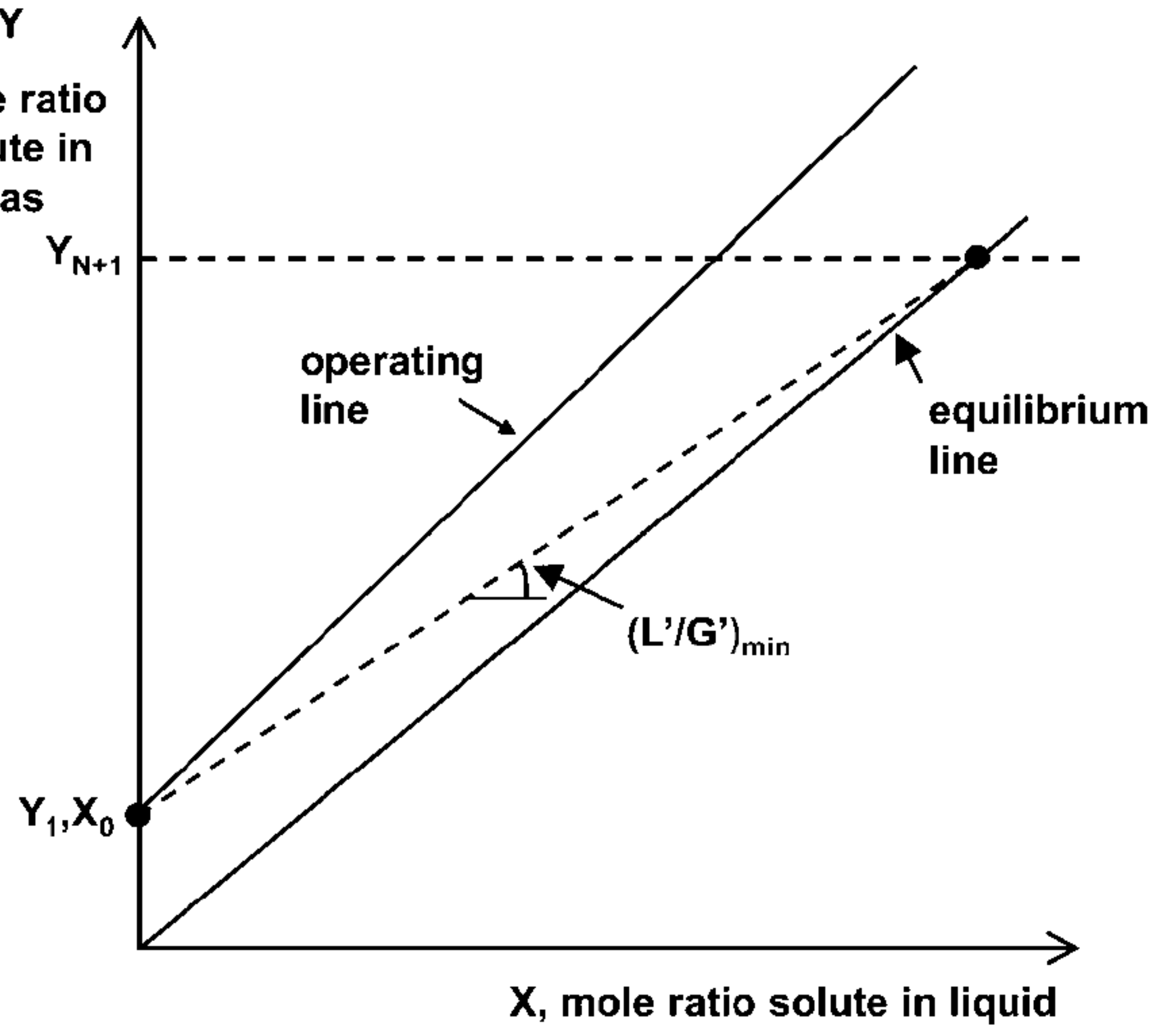
Operating Lines for Absorption



McCabe-Thiele diagram for absorption

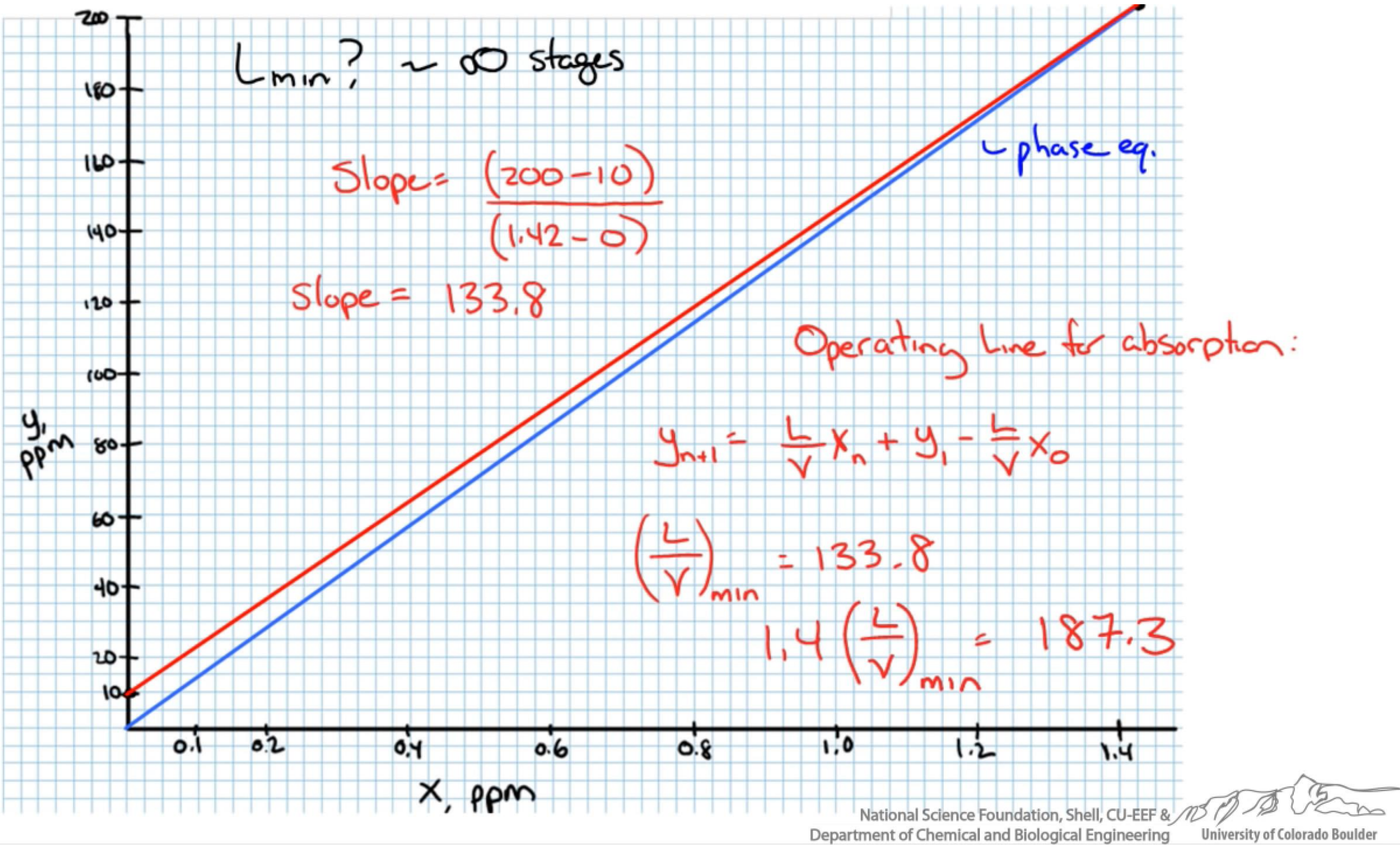
operating line in absorption is above the equilibrium line

Absorption and Stripping



McCabe-Thiele diagram for minimum L/G ratio for absorption

Absorption and Stripping



L_{min}? ~ ∞ stages

$$\text{Slope} = \frac{(200-10)}{(1.42-0)}$$

Slope = 133.8

Operating Line for absorption:

$$y_{n+1} = \frac{L}{V}x_n + y_1 - \frac{L}{V}x_0$$

$$\left(\frac{L}{V}\right)_{min} = 133.8$$

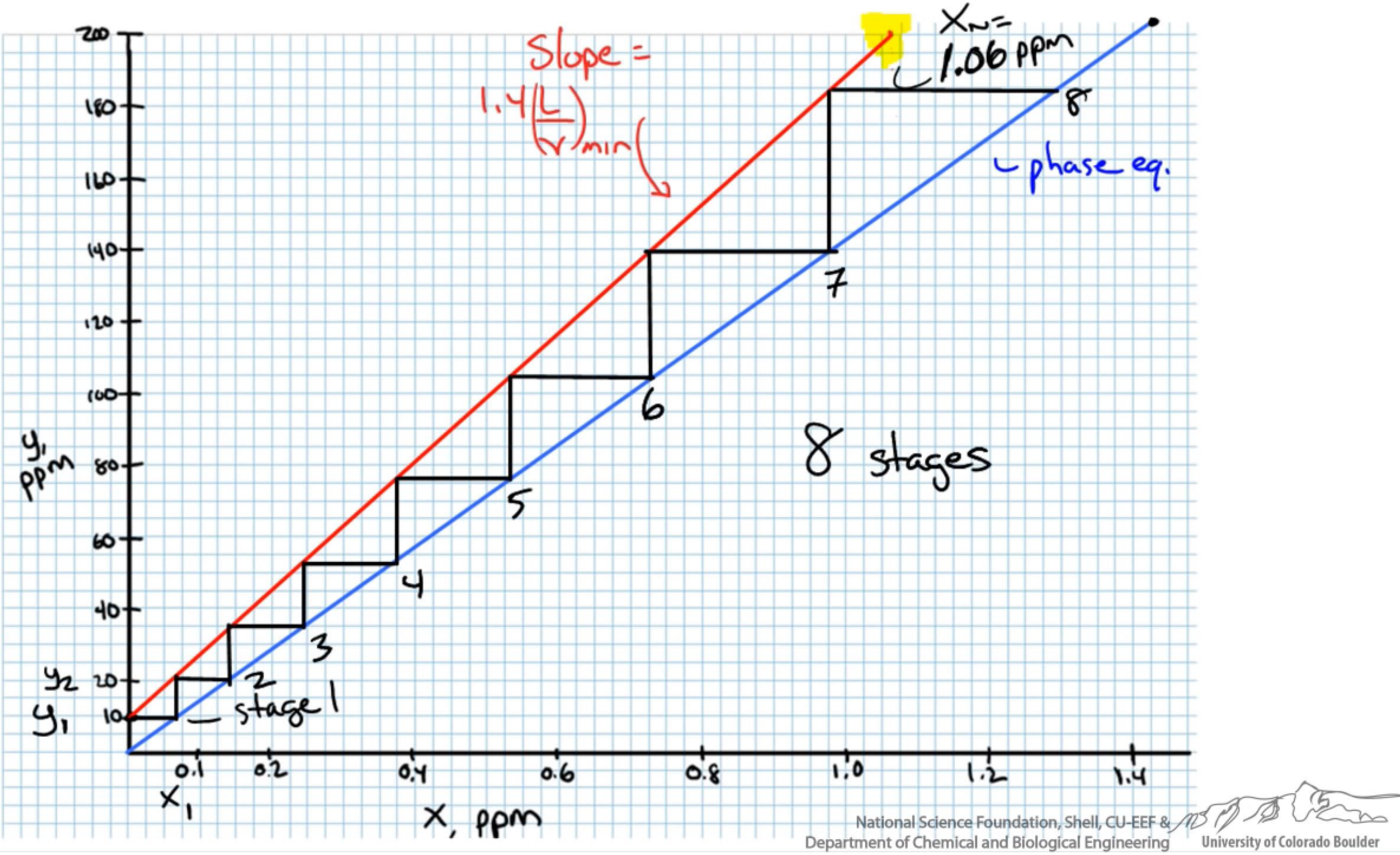
$$1.4\left(\frac{L}{V}\right)_{min} = 187.3$$

National Science Foundation, Shell, CU-EEF &
Department of Chemical and Biological Engineering
University of Colorado Boulder

McCabe-Thiele diagram for minimum L/G ratio for absorption

NSF, Shell, and CU Boulder Chem.Eng. https://goo.gl/ZPT1kC

Absorption and Stripping

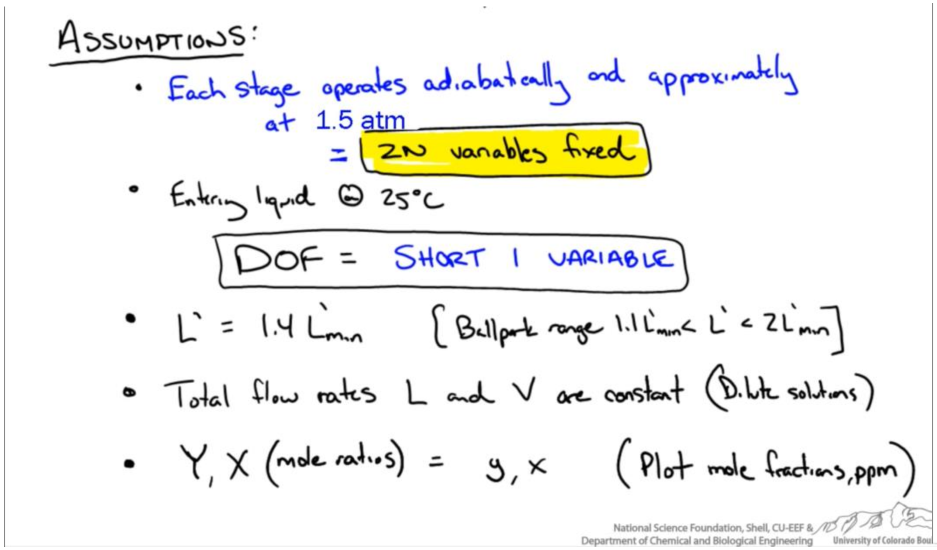


McCabe-Thiele diagram for minimum L/G ratio for absorption

NSF, Shell, and CU Boulder Chem.Eng. https://goo.gl/ZPT1kC

Absorption – Note in example:

You won’t need to determine # variables or DOF,



ASSUMPTIONS:

- Each stage operates adiabatically and approximately at 1.5 atm
  = 2N variables fixed
- Entering liquid @ 25°C
  DOF = SHORT 1 VARIABLE
- $L' = 1.4 L'_{min}$ [Ballpark range $1.1 L'_{min} < L' < 2 L'_{min}$]
- Total flow rates L and V are constant (Dilute solutions)
- Y, X (mole ratios) = y, x (Plot mole fractions, ppm)

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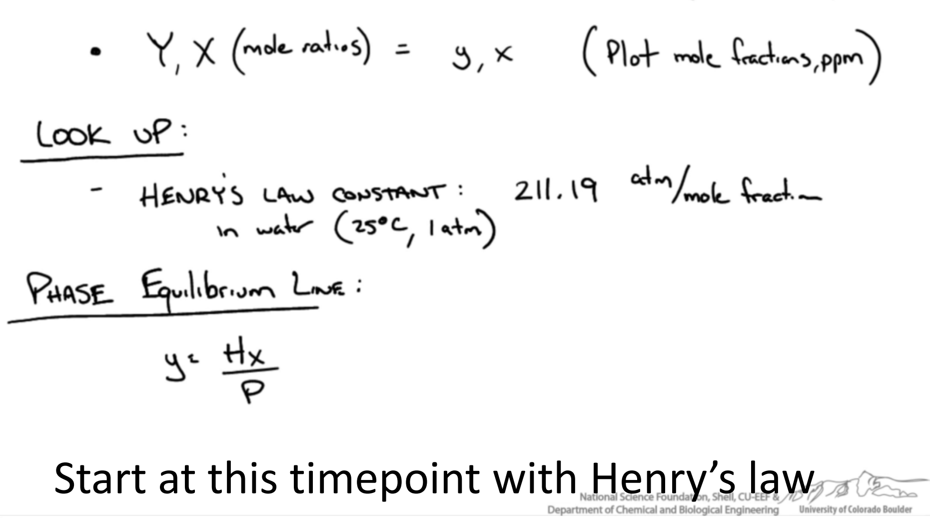
https://youtu.be/BoPKngZZwVI?t=317



- Total flow rates L and V are constant (Dilute solutions)
- Y, X (mole ratios) = y, x (Plot mole fractions, ppm)

LOOK UP:

- HENRY'S LAW CONSTANT: 211.19 atm/mole fraction in water (25°C, 1 atm)

PHASE Equilibrium LINE:

$$y = \frac{Hx}{P}$$

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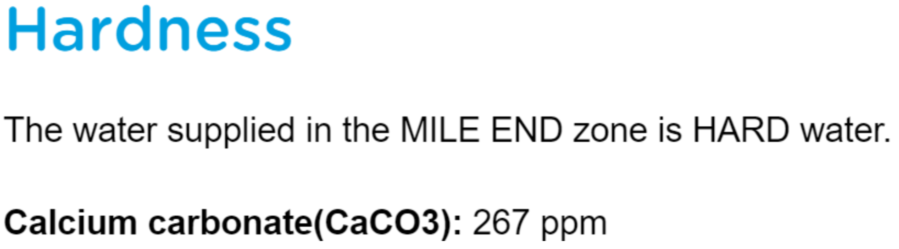
Start at this timepoint with Henry’s law
And try to solve the problem.
https://youtu.be/BoPKngZZwVI?t=349

The example is done step-by-step in detail also graphically, and you see a lot of the correspondences with the McCabe-Thiely analysis for distillation.

How Long Does a Filter Last?

https://www.thameswater.co.uk/help-and-advice/water-quality/check-the-water-quality-in-your-area

Calculate life for a C150 filter with 267 ppm water?



Hardness

The water supplied in the MILE END zone is HARD water.

Calcium carbonate(CaCO3): 267 ppm

PURITY C Finest	C150	C500
Technology	softening	
Capacity¹ with a total hardness of 10 °dH and 0 % bypass²	1.100 l	3.414 l
Max. operating pressure	8,6 bar	
Water intake temperature	4 – 30 °C	
Flow at 1 bar pressure loss	145 l/h	140 l/h
Nominal flow	60 l/h	100 l/h
Pressure loss at nominal flow	0.25 bar	0.5 bar
Dimensions (W/D/H) Filter head with filter cartridge	117/104/419 mm	144/144/557 mm
Weight (dry/wet)	1.8/2.8 kg	4.6/6.9 kg

10 dH = 178 ppm, so Capacity = 1100 L *178 mg/L = 196g $CaCO_3$

so x = 196 g / 267 mg/L = 734 L And it costs £74

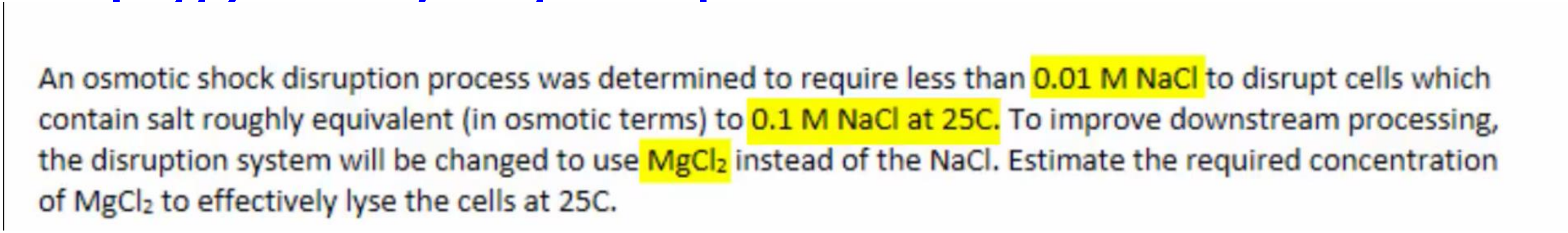
So £74 / 734 L = £0.10 / L – for good tasting and no-scale water

If it cleans molecular ions, does it also filter bacteria and viruses?

Osmotic Pressure

Osmotic pressure determined for different salts:

https://youtu.be/AGRjXcB14qA?list=PL61BFC1C064B40049&t=31



An osmotic shock disruption process was determined to require less than 0.01 M NaCl to disrupt cells which contain salt roughly equivalent (in osmotic terms) to 0.1 M NaCl at 25C. To improve downstream processing, the disruption system will be changed to use $MgCl_2$ instead of the NaCl. Estimate the required concentration of $MgCl_2$ to effectively lyse the cells at 25C.

See if you can first solve the problem yourself,
Then continue the video to see the solution if you need to.

Drying – Terminology and Learning Goals

By the end of this lecture you'll be able to: **drying.** (how prosaic!) Yet, in a quantitative way in which none of your friends outside this class would be able to.

Say what are **wet-bulb temperature, absolute humidity, relative humidity, .**
Other vocabulary: **Chilton-Colburn transfer numbers for heat and mass,**
See this concise summary: https://www.youtube.com/watch?v=7YlQ_4jL_gs

We'll identify **Drying Mechanisms** and

Derive **simplified rate equations** to **estimate drying times**

Discuss **Drying Methods** and **Drying Equipment**

Applications in: Foods, building materials, powders, papers, fabrics

Discuss Efficiency and cost –
Drying vs. unnecessary transportation of products containing water

Bread Rusk and Hair Drying

Need to strike an optimum balance between
Temperature and Drying Rate

Drying – Wet Bulb Temperature

When the amount of air >> amount of evaporated moisture
The dynamic equilibrium (non-equilibrium steady state)
Temperature of a wet surface is called T_{wb}, the **wet-bulb temperature**

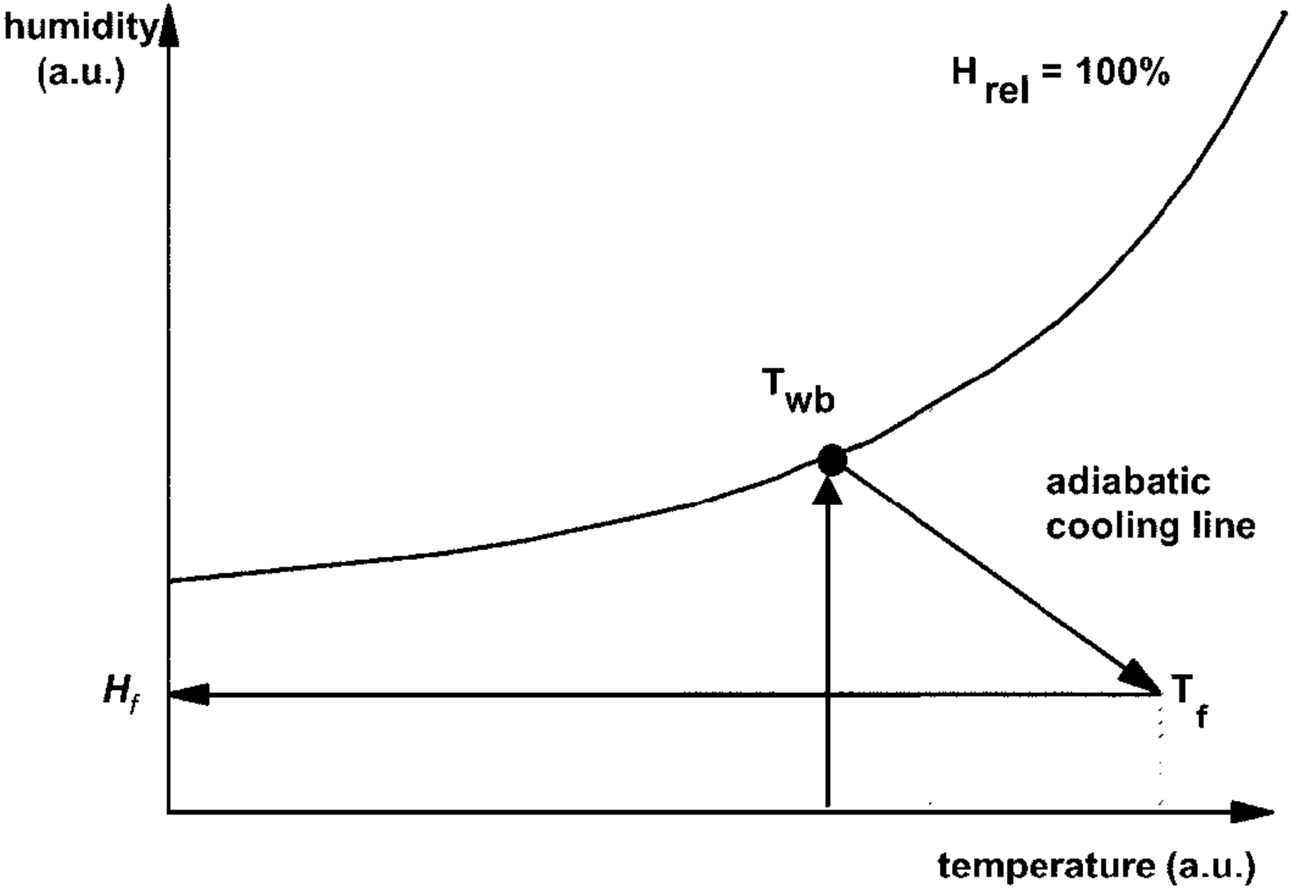
$$\Phi_{vap} \cdot \Delta H_{vap} \quad = \quad h\,(T_f - T_{wb}) \qquad \text{units [J s}^{-1}\text{ m}^{-2}\text{]}$$

Drying rate *Energy transfer*
Energy *from the surface*

where
h = heat transfer coefficient (convection) [W m^{-2} K^{-1}]
ΔH_{vap} = molar heat of evaporation [K]

Examples – Passive cooling in non-glazed pottery
T_{wb} indicates max amount of vapor that can be carried the dry gas

Air Humidity – From Wet-Bulb Temp.



Relating Wet and Dry-bulb temperatures – via adiabatic cooling lines

Psychrometric Chart

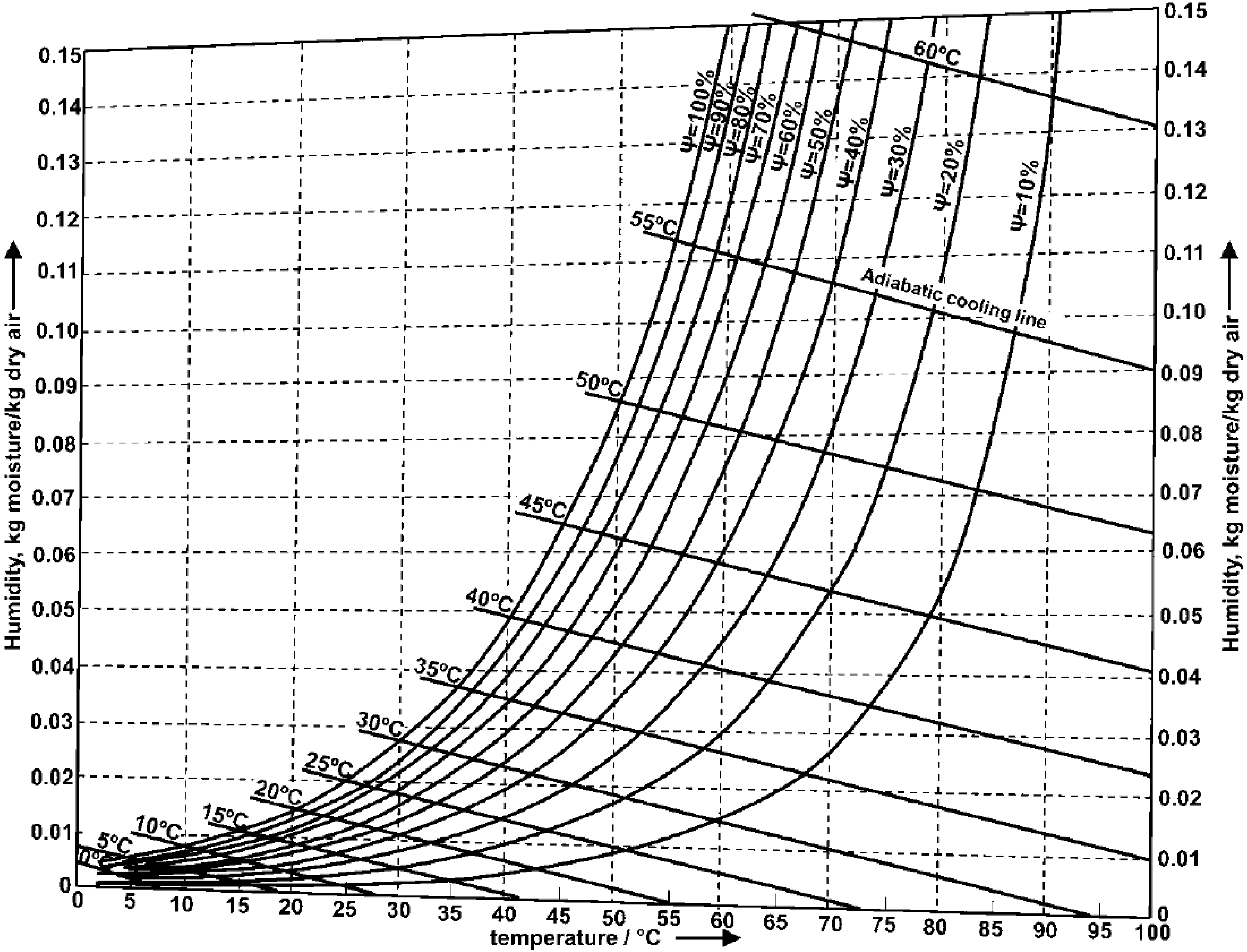
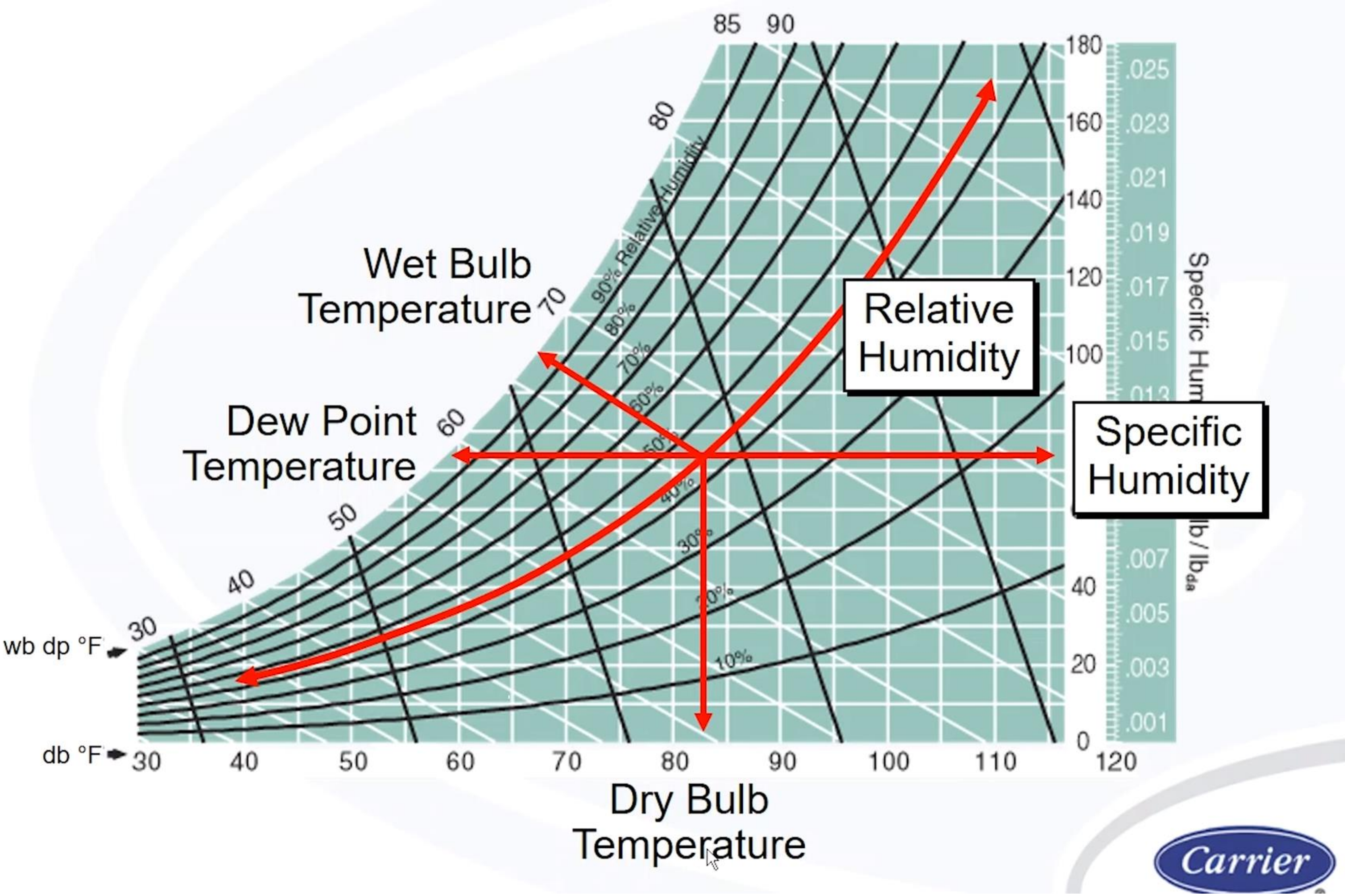


Fig. 7.3 Psychrometric chart of air-water at 1 bar total pressure (adapted from [56]).

Properties of Air - Psychrometric Chart



Wet Bulb Temperature

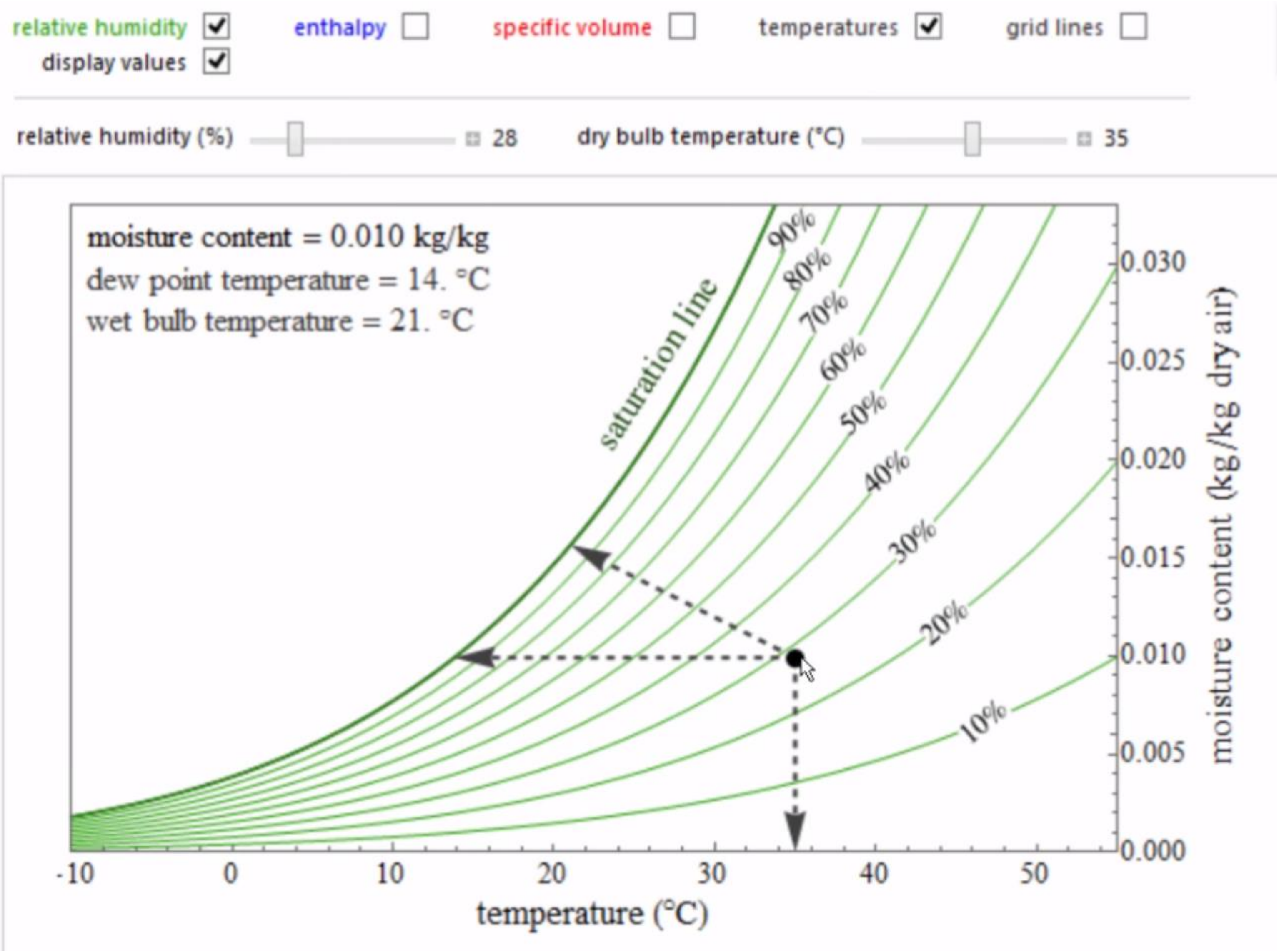
Dew Point Temperature

Relative Humidity

Specific Humidity

Dry Bulb Temperature

Psychrometric Chart - Interactive



relative humidity ☑

display values ☑

enthalpy ☐

specific volume ☐

temperatures ☑

grid lines ☐

relative humidity (%) 28

dry bulb temperature (°C) 35

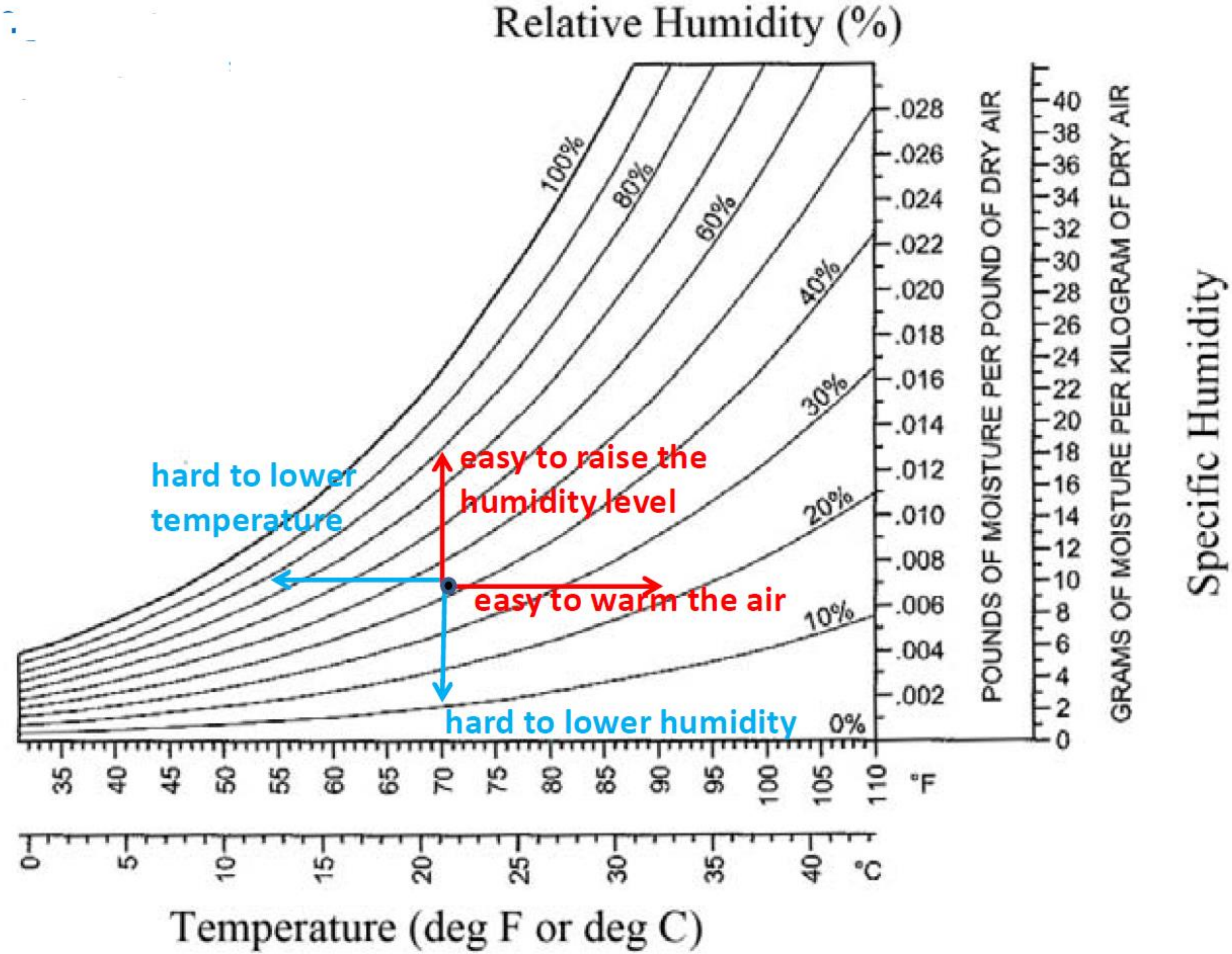
moisture content = 0.010 kg/kg

dew point temperature = 14. °C

wet bulb temperature = 21. °C

https://youtu.be/IVwniWExPgA?t=207

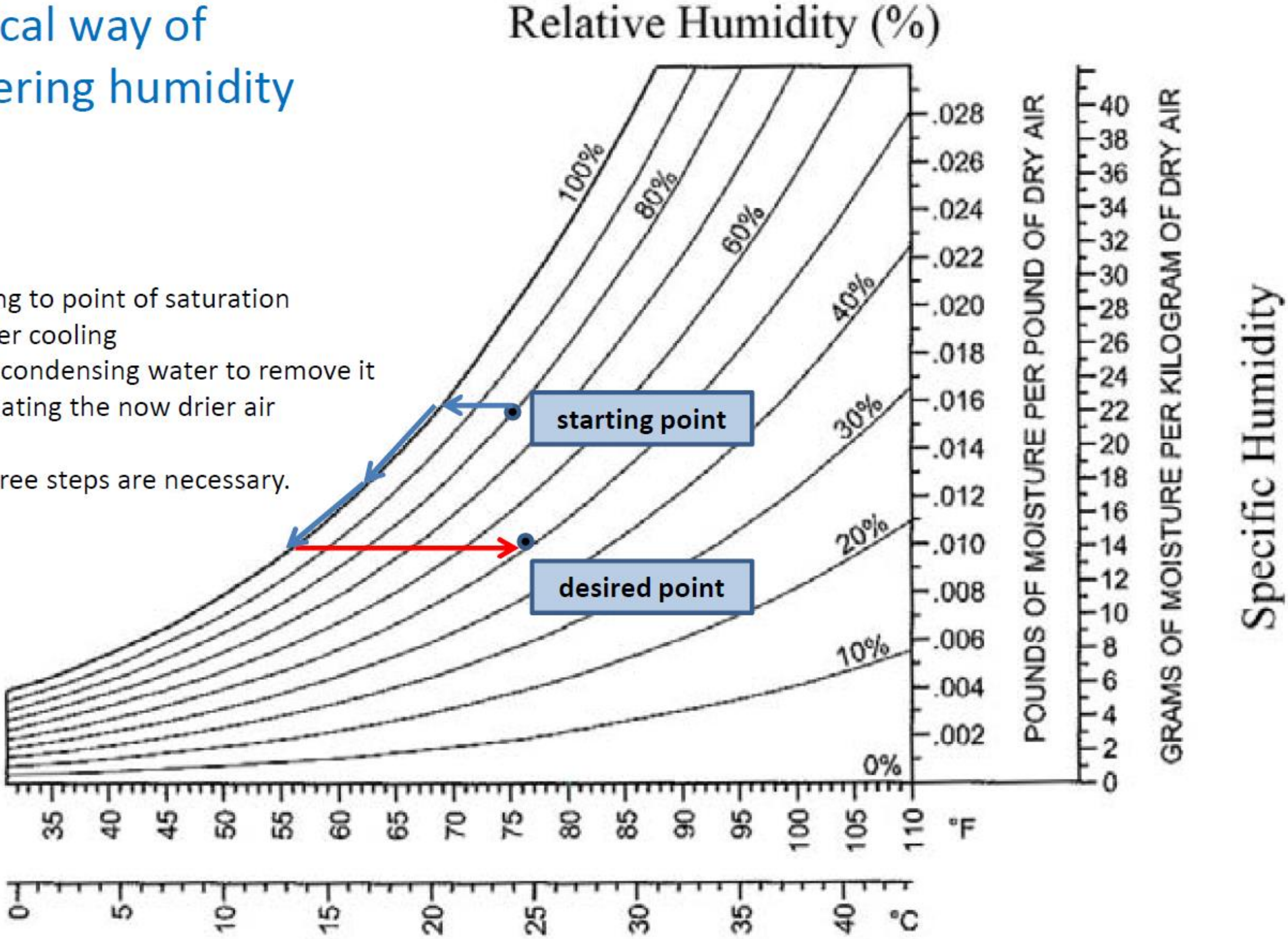
Psychrometric Chart - Practice



Typical way of lowering humidity

1. Cooling to point of saturation
2. Further cooling while condensing water to remove it
3. Re-heating the now drier air

Thus, three steps are necessary.



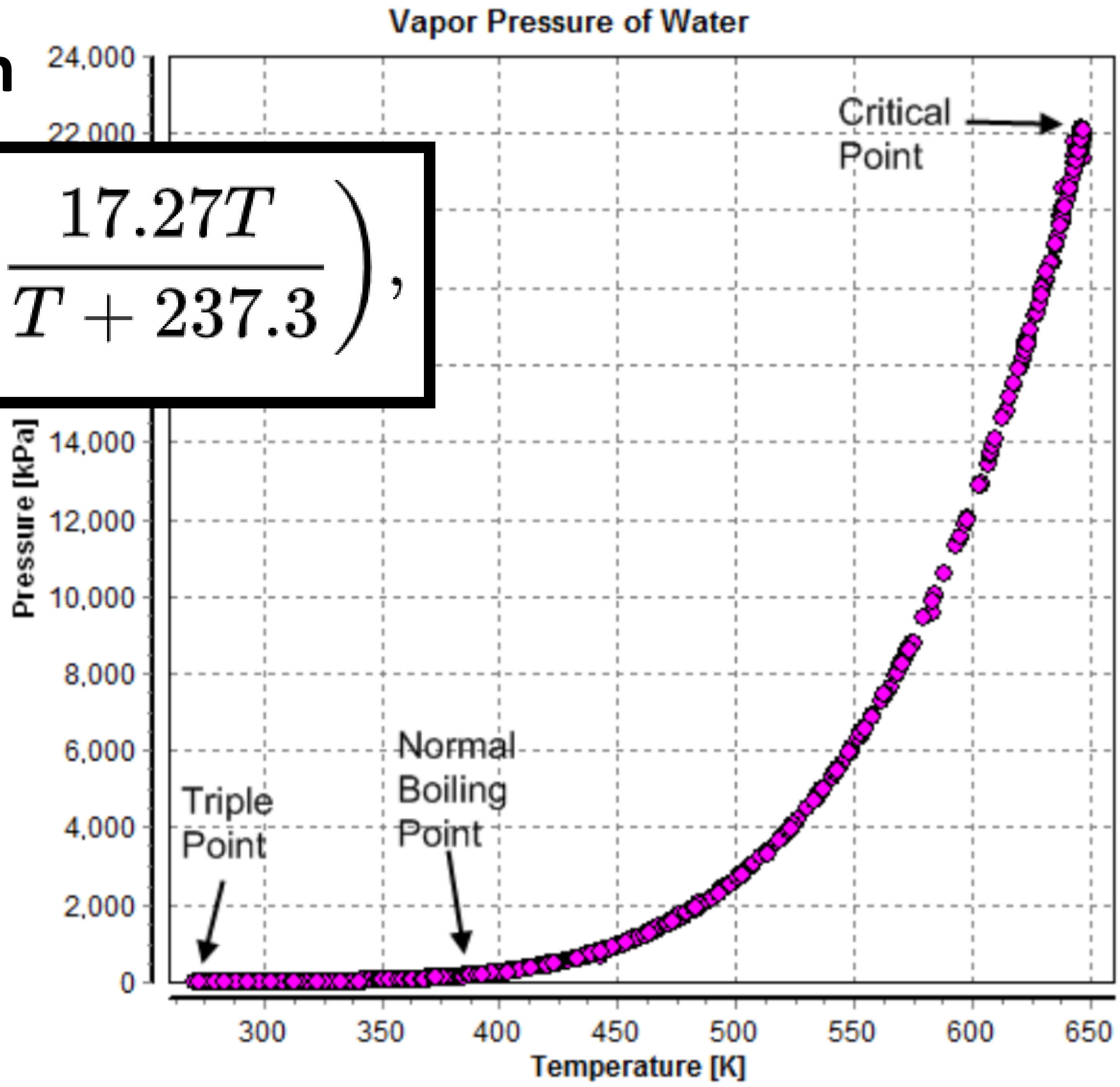
Saturation Vapor Pressure of Water

The Tetens equation

$$\boxed{P = 0.61078\,\exp\left(\frac{17.27T}{T+237.3}\right),}$$

where
T = temperature in °C
and *P* = pressure in kPa

Above form valid for
T > 0 °C



Experimental data taken from Dortmund Data Bank

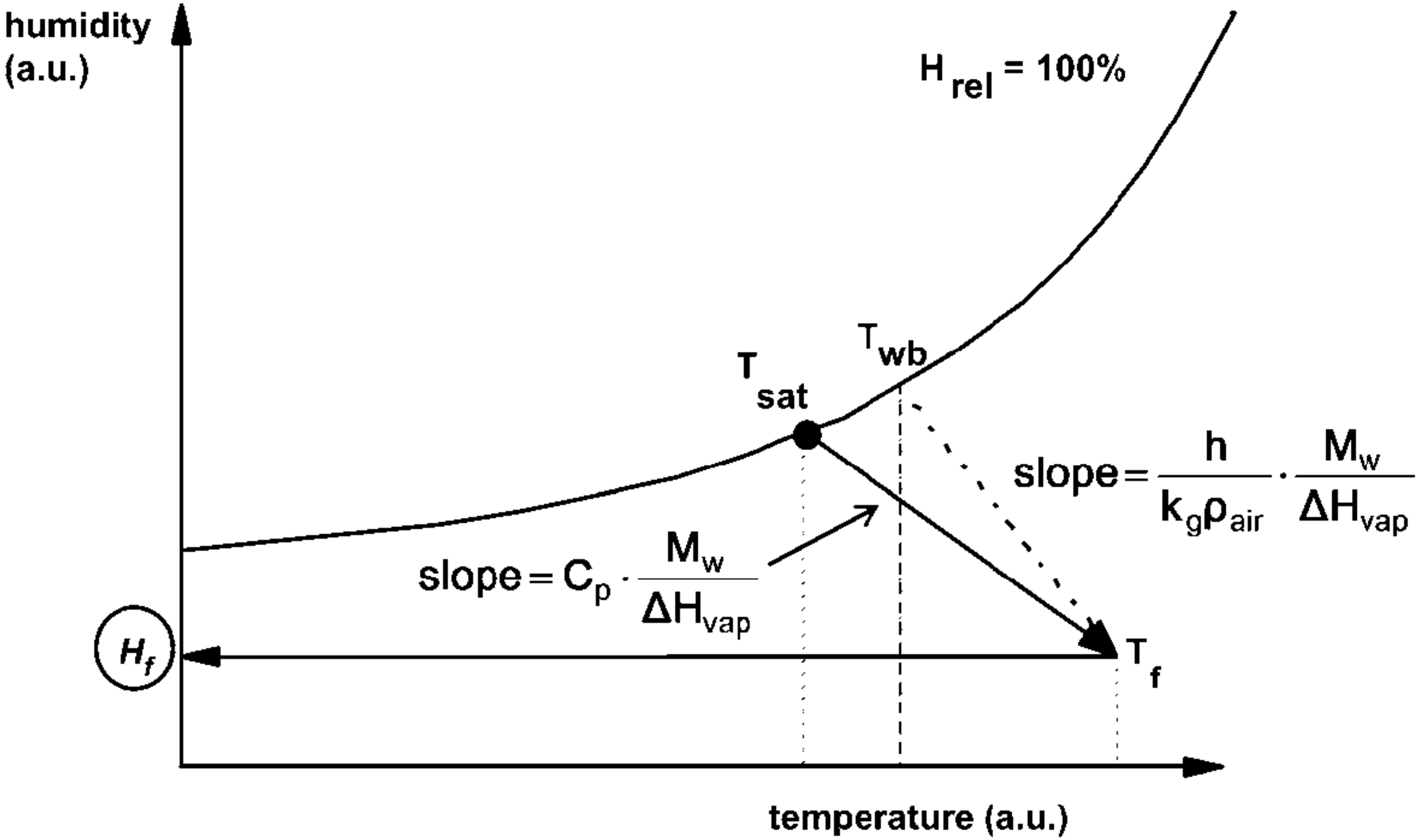
Drying – Slowly at Low Vapor Pressures

For low drying rates, and
low vapor concentrations c,
drying rate Φ_{vap} is proportional
to the driving force $(c_{sat(Ts)} - c_f)$

Drying rate Φ_{vap} $= k_g\,(c_{sat(Ts)} - c_f\,)$
units [mol s^{-1} m^{-2}]

where
T_f = temperature of heated air (with concentration c_f)
T_s = temperature of wet surface [K]
c_{sat} = saturation vapor (water) concentration at T_s [mol m^{-3}]
c_f = vapor (water) concentration in *feed* gas (air) [mol m^{-3}]
k_g = mass transfer coefficient [m s^{-1}]

Air Humidity – From Wet-Bulb Temp.



When stream of air Φ_{air} at T_f is mixed thoroughly and adiabatically, with liquid at T_{sat}, it leaves completely saturated with vapors (@Tsat)

Drying – Wet Bulb Temperature

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The dynamic equilibrium (non-equilibrium steady state)
Temperature of a wet surface is called T_{wb}, the **wet-bulb temperature**

$$\Phi_{vap} \cdot \Delta H_{vap} \quad = \quad h\,(T_f - T_{wb}) \qquad \text{units } [\mathrm{J\ s^{-1}\ m^{-2}}]$$

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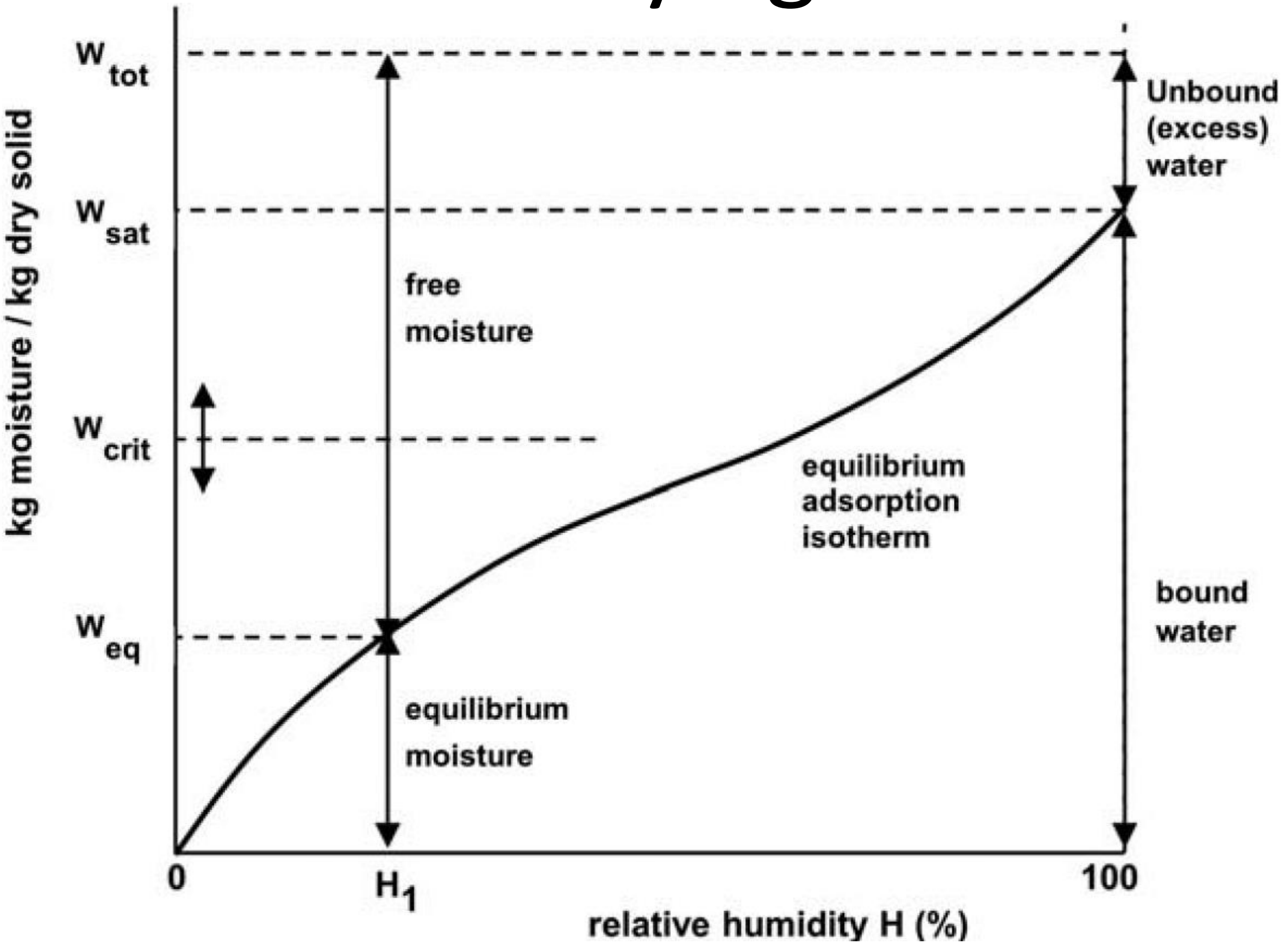
Examples – Passive cooling in non-glazed pottery
T_{wb} indicates max amount of vapor that can be carried the dry gas

Drying Solids



Unbound vs. Free Moisture

Bound/Unbound Water and *Structure of the solid* – lead to different drying regimes and mechanisms

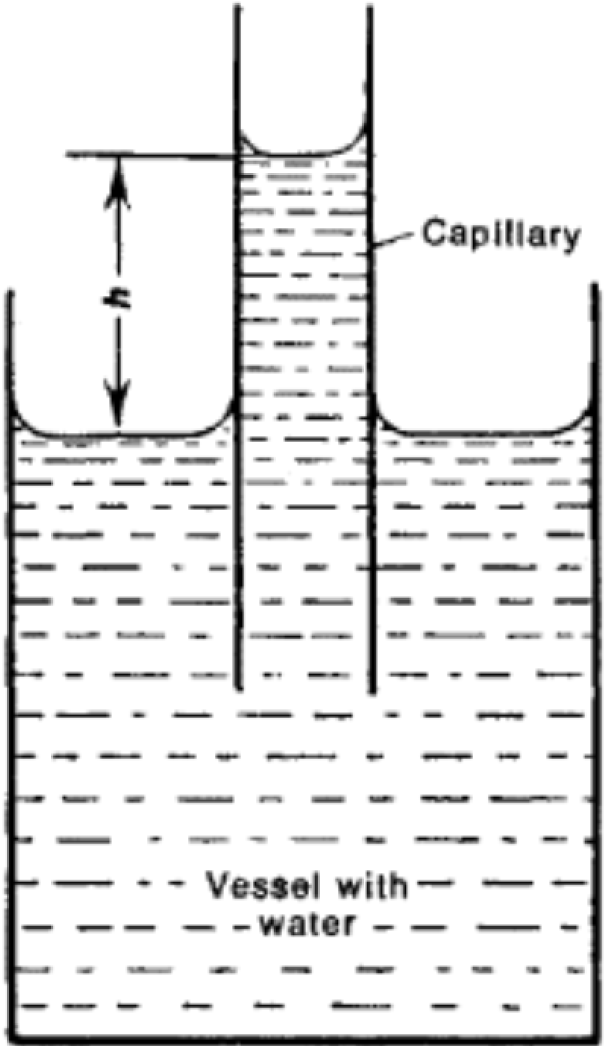
Drying Solids – Water in Pores

$$p_{sat} = p_{sat}^{\infty} \exp \frac{V_{liq}(P_{liq} - P)}{RT}$$

where V_{liq} = molar volume of liquid.

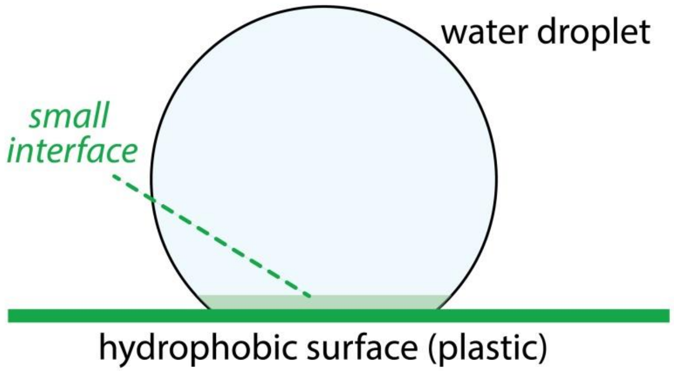
Pressure in the liquid can affect pressure above it

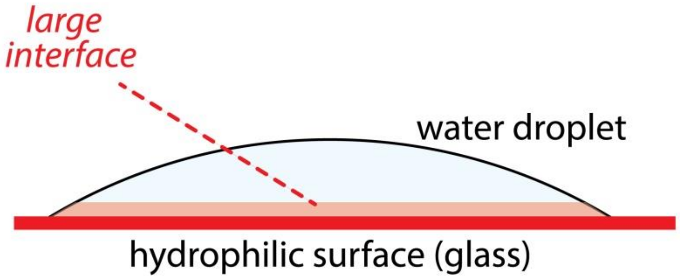
$$P_{liq} - P = \gamma \left(\frac{1}{r_1} + \frac{1}{r_2} \right)$$



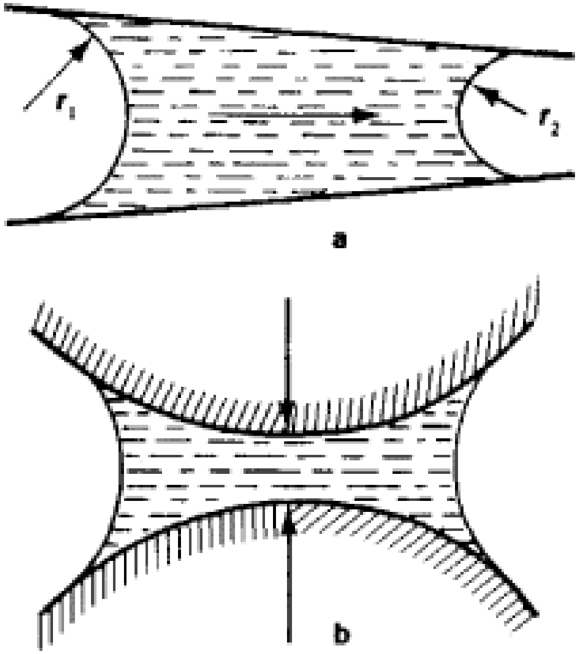
Pressure in curved geometries – from Laplace Eqn.

Pressure in Droplets vs Bubbles



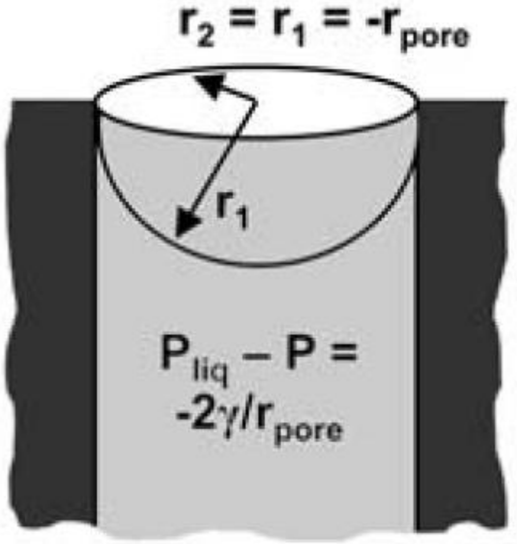


$$\Delta P = \gamma\left(\frac{1}{r_1}+\frac{1}{r_2}\right)$$

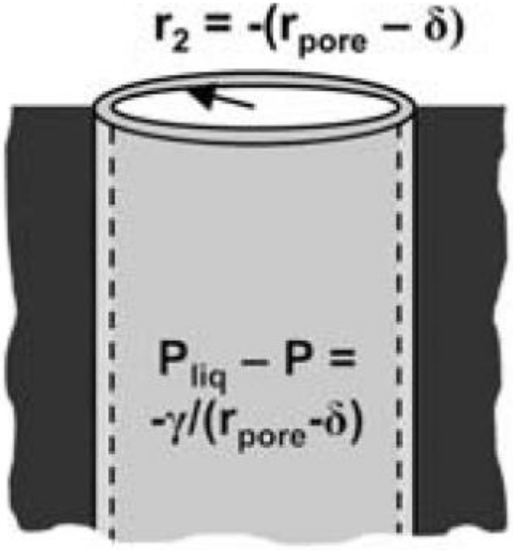


Pressure in curved geometries – from Laplace Eqn.

Pressure in Bubbles and Pores



$$p_{sat} = p_{sat}^{\infty} \exp\left(-\frac{V_{liq}}{RT}\frac{2\gamma}{r_{pore}}\right)$$

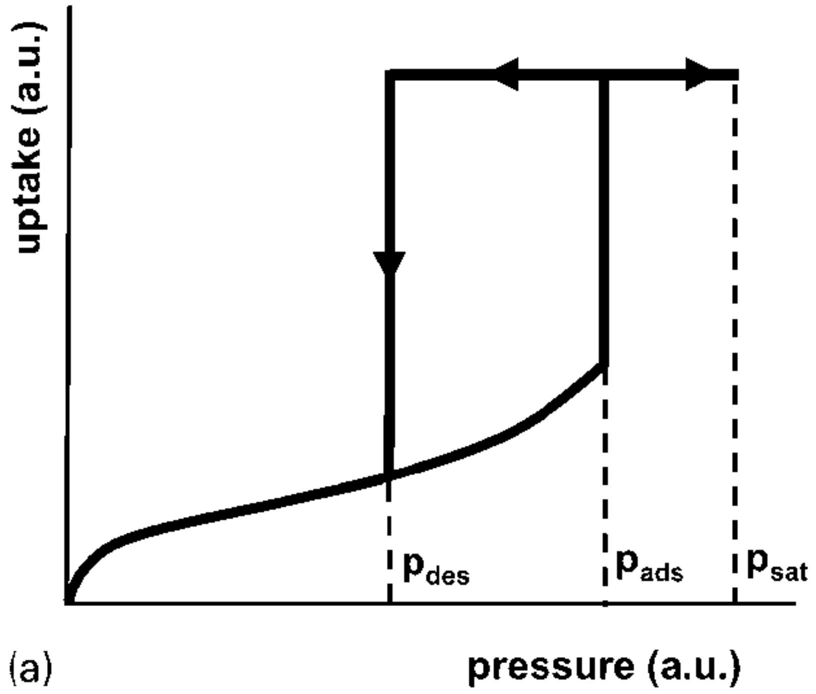


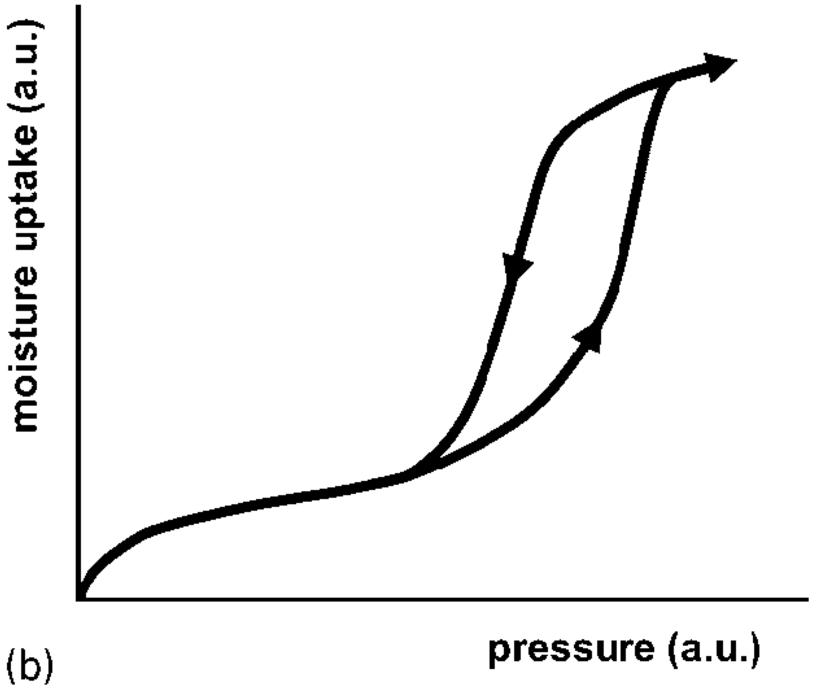
$$p_{sat} = p_{sat}^{\infty} \exp\left(-\frac{V_{liq}}{RT}\frac{\gamma}{r_{pore} - \delta}\right)$$

Pressure to empty pore

Pressure to Fill pore

Drying Porous Solids





Ideal Cyllinder Pores **Irregular Pores**

Adsorption/ desorption hysteresis