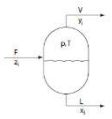
TKP4105 (Sep-tek.)
Ch. 11
VLE and Flash slides

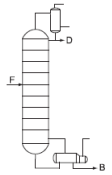
Sigurd Skogestad

Chapter 11. Vapor-Liquid Separation Processes

- **Introduction (Diffusion is slow!)**
- **Flash and VLE (Skogestad lectures 1+2+3)**
  - Simple separations
  - Oil/gas-separation offshore (series of simple flashes with decreasing pressure)



- **Distillation (lectures 4+5+6+7)**
  - The most important separation process for liquids
  - About 7% of industrial usage of energy is for distillation!
  - Oil refing, synfuels
  - Petro- og fine chemicals
  - Air separation



- **Lectures 8-12: ”Gas”-liquid separation processes (Ch. 10) Absorption and stripping**
  - Example: CO2-removal using amine solutions

Diffusion is slow!

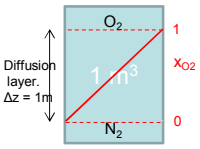
Ficks law (Mass transfer by diffusion):

$$J_{Az} = -D_{AB}\frac{dc_A}{dz} \quad [\frac{\text{mol}}{\text{m}^2.\text{s}}]$$

To get mass flow $\dot{m}_A$ [kg/s] multiply by $S[\text{m}^2] \cdot \text{M}_\text{A}[\frac{\text{molA}}{\text{kgA}}]$
Use $c_A = x_A c_{tot}$ and $c_{tot} M_A = \rho$ (assuming $M_A = M_{tot}$):

$$\dot{m}_{Az} = -D_{AB} \cdot \rho \frac{dx_A}{dz} S \quad [\frac{\text{kg}}{\text{s}}]$$

Typical data gas (1 bar): $D_{AB}\rho = 10^{-5}\frac{m^2}{s} \cdot 1\frac{kg}{m^3} = 10^{-5}\frac{kg}{s \cdot m}$
Typical data liquid: $D_{AB}\rho = 10^{-9}\frac{m^2}{s} \cdot 10^{3}\frac{kg}{m^3} = 10^{-6}\frac{kg}{s \cdot m}$
Example gas. Concentration difference: $\Delta x_A = 1$ (max).
Diffusion layer: $\Delta z = 1$ m. Surface area: $S = 1m^2$. $\Rightarrow m_A = 10^{-5} kg/s$
Process applications: Want $m_A \approx 1$ kg/s. **Need $S/\Delta z$ a factor 10^5 larger!!**



IN PRACTISE: Mass transfer between phases (including distillation):

- USE INTENSIVE MIXING to get small Δz (small boundary layer)
- + use large surface area S between phases

Class quiz (1)

1. How much CO2 gas [liter] in1 liter coke?
2. What is the equilibrium pressure for coke?
   - Data: Temperature=25C
   - CO2 concentration in coke is about 5 g/l (about 0.5 wt%).
   - VLE: Water-CO2 at 25 C has Henry's constant (Hco2) = 1670 bar.
     Vapor pressure of water at 25C is about 0.03 bar.
   - Mole weight water = 18 g/mol
   - Mole weight CO2 = 44 g/mol

- Solution:

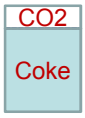
- **Question 1.** 1 liter coke contains n=5g / 44g/mol = 0.114 mol C02

- **Question 2.**
- x_{co2} = mole fraction CO2 in liquid
- From data (0.5 wt% CO2): x_{co2} = 0.5g/ (44 g/mol) / [95g/18 g/mol + 5g/44 g/mol] = 0.0021
- **Assume vapor-liquid equlibrium:**
- Partial pressure of CO2 from Henry's law:
- Partial pressure of H2O from Raoults's law:
- Total pressure,
  - google: Typical filling pressure for CO2 is about 8 bar (but equlibrium is not reached)

Class quiz (2)

3. Is the pressure really 3.53 bar inside a coke bottle?

4. Why not?
   Answer: because of slow diffusion



3. How can we increase the pressure?

Answer:
- Shake (so do not keep coke in refrigerator door)
- Mentos!

Experiment

- Skru av korken… det er litt overtrykk….kommer ut litt gass (CO2), men neppe 2.8 liter. ..
- Hvorfor kommer ikke resten ut?.....
- Hvordan få ut mer?...
- Riste
- eller bedre: Menthos
- Let us try!

White Mentos + Diet Coke = Explosion

- **Mythbusters Status: True (Discovery Channel, 09 Aug. 2006)**
- http://www.museumofhoaxes.com/hoax/weblog/comments/3600/P20/
- Given the urban legend about kids eating pop rocks and soda, and then having their stomachs explode, I wouldn't have believed that mixing Mentos and soda could cause such a violent reaction. But after watching the video posted on WLTX's website, I do. (You need Windows Media Player to view it, and I had to click the "Trouble Viewing" button to make it work.) To summarize what the video shows, three Mentos are dropped into a bottle of soda, causing a geyser of soda to shoot up about three or four feet high out of the bottle. WLTX provides this scientific explanation for the phenomenon:

  Mentos contains a chemical known as ARABIC GUM (this is the ingredient that makes the mint "chewy"). This ingredient causes the surface tension of the water molecules to break even more easily, releasing more carbon dioxide gas at an astounding rate! .....The gas causes pressure to rapidly build inside the bottle which thrusts the soda upwards in a wonderful fountain-like BLAST!
- Posted By: Alex | Date: *Fri Sep 23, 2005* | Permalink | Total Comments: 184
  Category: Food

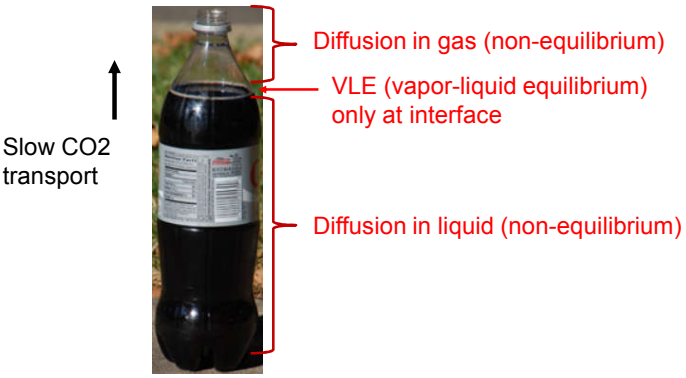
- Adresseavisen Ida Alvsen Publisert: 24.07.2010 kl. 13:30
- Vi prøver å lage en Mentos-Cola light-fontene.
  Et kjent og kjært triks prøvd av utallige hjemmevideoentusiaster på Youtube, for ikke å snakke om Mythbusters på Discovery Channel.
- Daniel Greiner Edvardsen, jan. 2011: Need to use WHITE Mentos
- Se også vitenwahl.no (bl.a. for bestilling av påfyllingsrør for Mentos)

Class quiz (3)

6. Why does pressure increase when we shake (or add Menthos)?
   - Shaking gives mixing and better mass transfer (do not need to rely on diffusion) … so approach equilibrium and CO_2 is released and pressure rises
   - Menthos give large surface area + low surface tension -> helps formation of CO_2-bubbles. These bubbles provide “artificial mixing” for further release of CO_2

Class quiz (4)

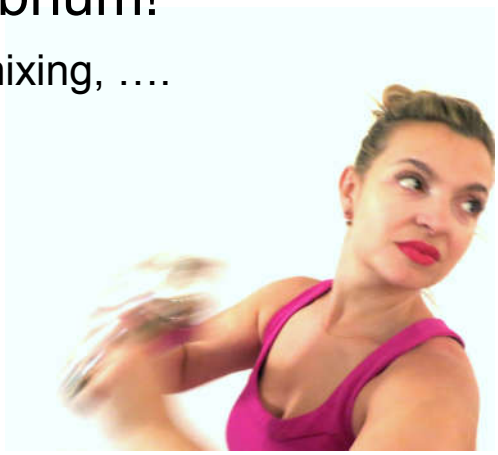
7. Why does not pressure stay high after shaking?
   - The CO_2 leaks out and equilibrium is not maintained because of slow diffusion



Diffussion is slow!

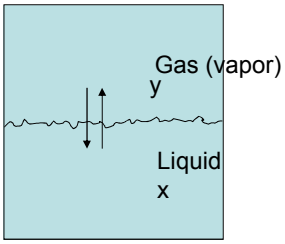
Lesson: Need to work hard to get equilibrium!

Shaking, mixing, ….



Equilibrium stage concept

- Assume well mixed (turbulence!) and large contact area so that there are no diffusion limitations for mass transfer
- Liquid and vapor phases* in equilibrium!



* the entire («bulk») phases

Vapor/liquid-equilibrium (VLE)

Partial pressure of component A: $p_A = y_A p$

Total pressure for mixture: $p = p_A + p_B + \cdots$

Raoult's law (ideal liquid): $p_A = x_A \; p_A^{\text{sat}}(T)$

Nonideal liquid: $p_A = \gamma_A \; x_A \; p_A^{\text{sat}}(T)$

Henry's law (dilute solution): $p_A = x_A H_A(T)$

- K-value. $K_i = y_i/x_i$

K is generally a function of: T, p, x, y

Raoult's law: $K_A = p_A^{\text{sat}}(T)/p$

Henry's law: $K_A = H_A(T)/p$

- Relative volatility, α (11.3B)

$$\alpha = \frac{K_A}{K_B} = \frac{y_A/x_A}{y_B/x_B}$$

Raoults law: $\alpha = \dfrac{p_A^{\text{sat}}(T)}{p_A^{\text{sat}}(T)}$

α can often be assumed constant (ideal mixture of simular components)!

Binary mixture

Given pressure

VLE diagrams. Binary mixture

TABLE 11.1-1. *Vapor-Pressure and Equilibrium-Mole-Fraction Data for Benzene–Toluene System*

Vapor Pressure							
Temperature		Benzene		Toluene		Mole Fraction Benzene at 101.325 kPa	
K	°C	kPa	mm Hg	kPa	mm Hg	x_A	y_A
353.3	80.1	101.32	760			1.000	1.000
358.2	85	116.9	877	46.0	345	0.780	0.900
363.2	90	135.5	1016	54.0	405	0.581	0.777
368.2	95	155.7	1168	63.3	475	0.411	0.632
373.2	100	179.2	1344	74.3	557	0.258	0.456
378.2	105	204.2	1532	86.0	645	0.130	0.261
383.8	110.6	240.0	1800	101.32	760	0	0

Txy-diagram

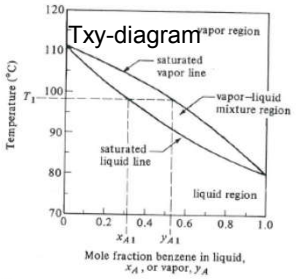
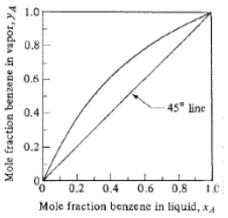


FIGURE 11.1-1. *Boiling point diagram for benzene (A)–toluene (B) at 101.325 kPa (1 atm) total pressure.*

FIGURE 11.1-2. *Equilibrium diagram for system benzene (A)–toluene (B) at 101.32 kPa (1 atm).*

xy-diagram (”equlibrium line”) (11.1B)



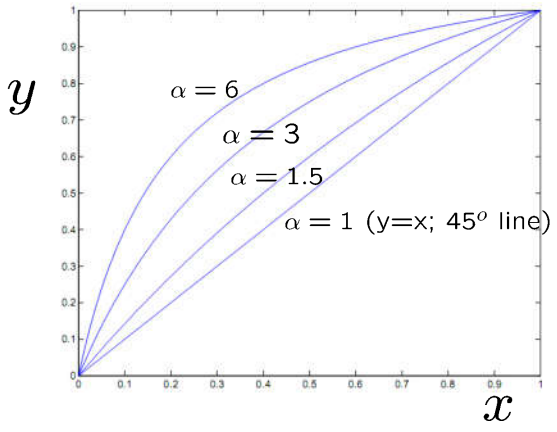
Ideal mixture

Given pressure

Constant relative volatility

- Binary mixture: $\alpha = \frac{y_A/x_A}{y_B/x_B} = \frac{y/x}{(1-y)/(1-x)} \Rightarrow y = \frac{\alpha x}{1+(\alpha-1)x}$

xy-diagram



Ideal mixture

Ideal mixture: Estimate of relative volatility (Sigurd's method)

$$\ln \alpha \approx \underbrace{\frac{\Delta H^{vap}}{RT_B}}_{\text{typical:}\approx 9-15} \cdot \frac{\Delta T_B}{T_B}$$

ΔH^{vap} - avg. heat of vap. at T_B [kJ/mol]

ΔT_B - boiling point difference [K]

T_B - geometric avg. boiling point [K]

Ref: King, Separation process, 2nd Ed. |980, p.680

- Example. iso-pentane (L) – pentane (H)

$T_L = 301.0$ K, $\Delta H_L^{vap} = 25$ kJ/mol,

$T_H = 309.2$ K, $\Delta H_H^{vap} = 27$ kJ/mol,

$\Delta T_B = 8.2$K, $T_B = \sqrt{301 \cdot 309.2} = 305.1$K,

$$\ln \alpha = \underbrace{\frac{\sqrt{25 \cdot 27} \cdot 1000}{8.31 \cdot 305.1}}_{10.2} \cdot \frac{8.2}{305.1} = 0.275; \quad \alpha \approx 1.32$$

Binary mixture

Given pressure

AZEOTROPES (y_A=x_A at some composition)

Max-boiling: Unusual.

Example: Formic acid-water

Min-boiling Common.

Example: Ethanol-water

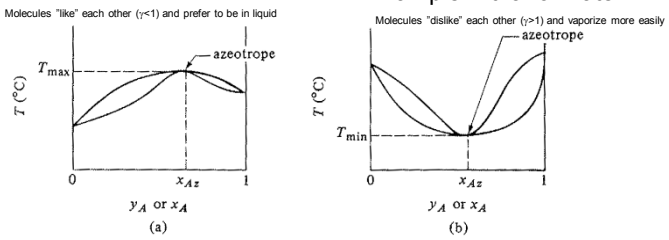
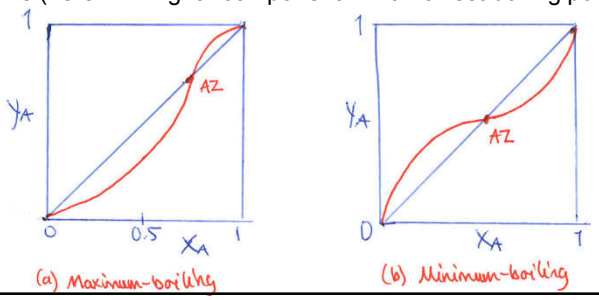


FIGURE 11.1-3. *Equilibrium boiling-point diagrams: (a) maximum-boiling azeotrope, (b) minimum-boiling azeotrope.*

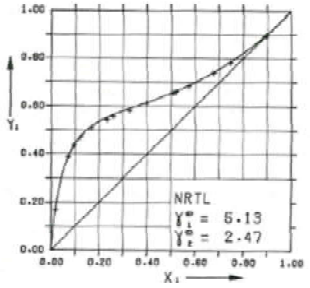
xy-diagrams (here: A= «light» component = with lowest boiling point):



Binary mixture | Given pressure

Ethanol-water at 1 atm: Minimum-boiling azeotrope at about x_1=0.90 (96 liquid volume-%)

```
(1) ETHANOL                                                  C2H6O
-------------------------------------------------------------------
(2) WATER                                                    H2O
-------------------------------------------------------------------

***** ANTOINE CONSTANTS              REGION *****          CONSISTENCY
(1)    8.11220 1592.864   226.184    20-  93 C    METHOD 1     +
(2)    8.07131 1730.630   233.426     1- 100 C    METHOD 2     +

PRESSURE=  760.00 MM HG   (  1.013 BAR  )

LIT: CAREY J.S.,LEWIS W.K.,IND.ENG.CHEM.24,882(1932).

CONSTANTS:      A12          A21        ALPHA12

MARGULES        1.6022       0.7947
VAN LAAR        1.6798       0.9227
WILSON        325.0757     953.2792
NRTL         -122.0876    1341.3195      0.3008
UNIQUAC        21.7366     262.9622
```



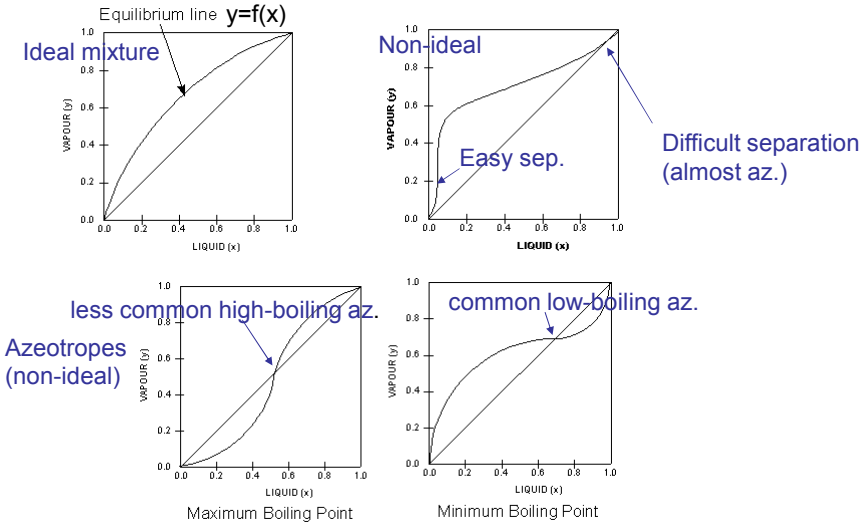
EXPERIMENTAL DATA			MARGULES		VAN LAAR		WILSON		NRTL		UNIQUAC	
T DEG C	X1	Y1	DIFF T	DIFF Y1	DIFF T	DIFF Y1	DIFF T	DIFF Y1	DIFF T	DIFF Y1	DIFF T	DIFF Y1
95.50	0.0190	0.1700	-0.05	0.0055	0.20	-0.0022	0.32	-0.0055	0.10	0.0008	0.19	-0.0017
89.00	0.0721	0.3891	0.39	0.0046	0.52	0.0027	0.47	0.0058	0.57	0.0018	0.54	0.0025
86.70	0.0966	0.4375	-0.10	0.0013	-0.09	0.0030	-0.23	0.0085	-0.00	0.0014	-0.06	0.0029
85.30	0.1238	0.4704	-0.04	-0.0065	-0.14	-0.0019	-0.34	0.0052	-0.03	-0.0035	-0.12	-0.0017
84.10	0.1661	0.5089	0.32	-0.0109	0.09	-0.0035	-0.13	0.0039	0.19	-0.0045	0.10	-0.0029
82.70	0.2337	0.5445	0.38	-0.0169	0.10	-0.0091	-0.06	-0.0037	0.17	-0.0085	0.10	-0.0080
82.30	0.2608	0.5580	0.37	-0.0152	0.10	-0.0082	-0.02	-0.0041	0.16	-0.0070	0.10	-0.0070
81.50	0.3273	0.5826	0.28	-0.0141	0.09	-0.0102	0.08	-0.0094	0.11	-0.0078	0.09	-0.0089
80.70	0.3965	0.6122	0.02	-0.0057	-0.05	-0.0062	0.03	-0.0081	-0.05	-0.0029	-0.05	-0.0049
79.80	0.5079	0.6564	-0.14	0.0015	-0.07	-0.0053	0.09	-0.0094	-0.09	-0.0015	-0.06	-0.0042
79.70	0.5198	0.6599	-0.17	0.0005	-0.09	-0.0068	0.09	-0.0109	-0.11	-0.0030	-0.08	-0.0057
79.30	0.5732	0.6841	-0.26	0.0026	-0.13	-0.0063	0.06	-0.0103	-0.16	-0.0028	-0.12	-0.0053
78.74	0.6763	0.7385	-0.30	0.0058	-0.10	-0.0046	0.11	-0.0066	-0.14	-0.0022	-0.09	-0.0039
78.41	0.7472	0.7815	-0.35	0.0010	-0.12	-0.0044	0.08	-0.0043	-0.16	-0.0031	-0.11	-0.0039
78.15	0.8943	0.8943	-0.26	-0.0057	-0.06	-0.0023	0.09	0.0011	-0.09	-0.0029	-0.05	-0.0021
MEAN DEVIATION:			0.23	0.0064	0.13	0.0051	0.15	0.0065	0.14	0.0036	0.13	0.0044
MAX. DEVIATION:			0.39	0.0169	0.52	0.0103	0.47	0.0109	0.57	0.0085	0.54	0.0089

Data: J. Gmehling and U. Onken. *Vapor-Liquid Equlibrium Data Collection*. Dechema. 1977

Binary mixture | Given pressure

SUMMARY. Vapor-liquid equilibrium (VLE) = ”Equilibrium line”

xy-diagrams:



Gibbs' phase rule for a system in equilibrium

- F = degrees of freedom that can be specified among the variables
  - Temperature*
  - Pressure*
  - Composition (of a given phase)
- F = 2 + C – P – R
  - C = no. components
  - P = no. of coexisting phases in equilibrium
  - R = no. of independent chemical reactions in equilibrium

Example. Ethanol-water in vapor/liquid equilibrium.
F = 2 + 2 – 2 – 0 = 2

1. Given $x_{ethanol}$=0.5 and p=1 atm: System is uniquely determined (cannot specify T)
2. Given $x_{ethanol}$=$y_{ethanol}$ (azeotrope) and p=1 atm: System is uniquely determined (cannot specify T)

* Book (10.2.A) does not state clearly that the rule involves the variables p and T

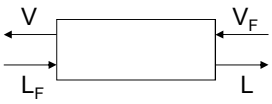
"Proof": There are originally 2 + (C-1) degrees of freedom among the variables temperature, pressure and composition. However, each extra phase or chemical reaction introduces an equation (equilibrium constraint) that reduces the degrees of freedom

11.2 Single-stage equlibrium contact for vapor-liquid system

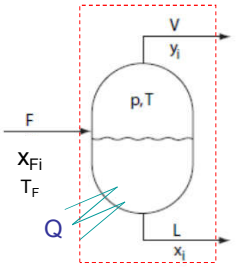
Flash

- **Flash: Products L and V in equlibrium**
  1. Important process in itself
     - Separators for mixtures with large relative volatility (Example: Offshore oil and gas)
  2. Building block for multistage processes

  Comment: *The book calls "flash" for "flash distillation" or "equlibrium distillation", but in the process industry the term "distillation" is used for multistage processes with reflux.*



- Here: Assume steady state (continuous operation)
- Equations:
  - N_c VLE equations:
    - $y_i = K_i x_i$ (i=1,2,…,N_c)
    - K_i: given function of **p,T,x_i,y_i**
  - N_c Component balanses (In=out, steady-state)
    - $Fx_{Fi} = Lx_i + Vy_i$ [mol/s] (i=1,2,…,N_c) [mol i/s]
  - 2 summation equations:
    - $\Sigma x_i = x_1 + x_2 + x_3 + \ldots. = 1$
    - $\Sigma y_i = y_1 + y_2 + y_3 + \ldots. = 1$
      (Also have total material balance F = L + V but not independent from the others)
  - 1 energy balance (In=out) *
    - $H_F + Q = H_L + H_V$ [J/s]
  - In total: $2N_c+3$ independent equations
- Unknowns with **given feed** (F, x_F, h_F):
  - $2N_c$+ 5 unknowns: x_i, y_i, V, L, p, T, Q
  - **Need 2 more specifications (e.g., p and T)**



* Energy balance: Normally not used in this course.
Often replaced ny "constant molar flows" assumption (gives V = V_F, L=L_F for adiabatic flash, Q=0)

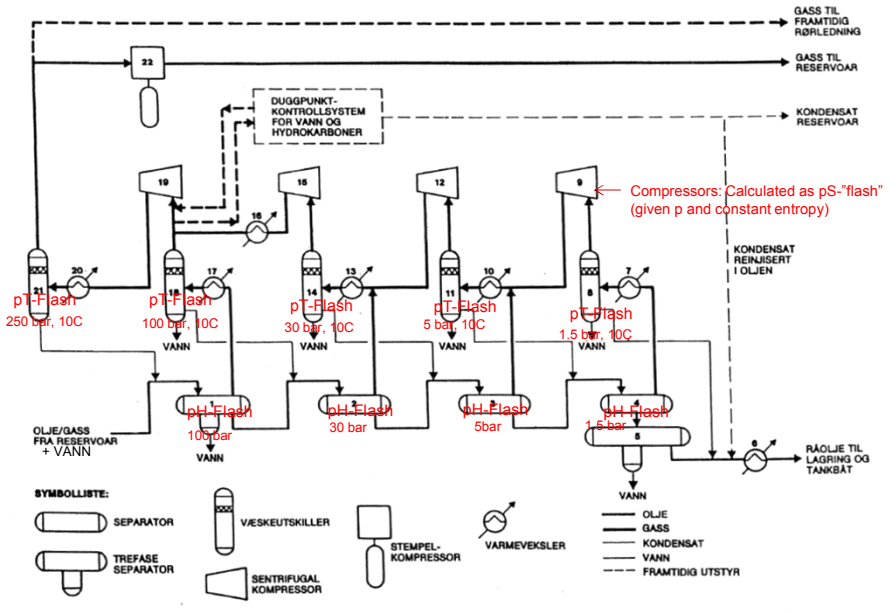
Example of flashes (given feed)

Need 2 more specifications:

- 1. Specify p + V/F
  - Analytical solution (constant α, see exercise) or graphical solution (any VLE, book 11.2)
  - Special cases:
    - 1A. Bubble point at given p (V/F=0). Book 11.7C-1
    - 1B. Dew point at given p (V/F=1) Book 11.7C-2
- 2. Specify T + V/F
  - Special case: 2A. Bubble point at given T (V/F=0), see exercise
  - Special case: 2B. Dew point at given T (V/F=1)
- 3. Specify p + T (pT-flash)
  - Iterative solution, book 11.7 (Rachford-Rice)
- 4. Specify p + H (H=H_F=enthalpy of feed for adiabatic flash)
  - Tank, adiabatic flash
  - Generally, need energy balance to find L and V:
    - $H \equiv H_L + H_V = H_F + Q$ [J/s]
  - Usually requires computer (Aspen, Hysys, Unisim…)
  - Comment. Stage in distillation column: pH-flash = p V/F-flash if we know liquid fraction in feed streams + assume constant molar flows.
- 5. Specify p + S

  - Compressor

Flytskjema Statfjord A



Flash calculations

- For more details, see my book
  - S. Skogestad, Chemical and Energy Process Engineering, CRC Press, 2009, Ch. 7.4
  - See: http://www.nt.ntnu.no/users/skoge/septek/lectures

- 1AB. Dew and bubble point. Numerical example. See exercise, Problem 2

(d) What is the saturation pressure (bubble point pressure) and vapor composiotion for a liquid mixture at 100C (373.2K) with 50 mol-% benzene and 50 mol-% toluene.

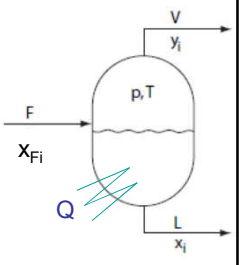
(e) Explain what a dew point is. Consider a gas mixture at 911 mmHg (1.21 bar) with 50 mol-% benzene and 50 mol-% toluene. What is the dew point temperature and what is the composition of the first liquid drop?

Binary mixture

Given pressure

1. p+V/F-flash

Analytical solution (const. α)



1. VLE at given p: Constant relative volatility
   - $y = \frac{\alpha x}{1+(\alpha-1)x}$
2. Component mass balance
   - $Fx_F = Lx + Vy$

Combine to get 2nd-order equation in x

$$Fx_F = Lx + V\frac{\alpha x}{1+(\alpha-1)x}$$

Example: F=150, x_F=0.50, α = 6 (propane-butane), V=80

Analytical solution: 75 = 70x + 80*6x/(1+5x)

350 x^2 + 175 x – 75 = 0

x = 0.2761

y = 0.6959

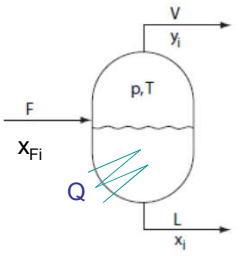
Analytical solution: Not in book
But relevant for exam!
See also Exercise.

Binary mixture

Given pressure

1. p+V/F-flash

Graphical solution (any VLE)

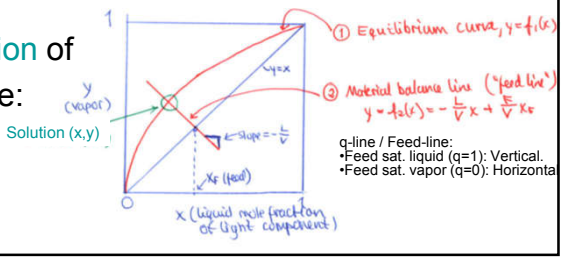


- **Book 11.2, example 11.2-1**

1. Equilibrium curve (given p)
   - $y = f_1(x)$
2. Component mass balance (”feed line”, ”q-line”)
   - $y = f_2(x) = -\frac{L}{V}x + \frac{F}{V}x_F = -\frac{q}{1-q}x + \frac{1}{1-q}x_F$

q = L/F = liquid fraction
1-q = V/F = vapor fraction

– Solution at intersection of VLE-curve & feed line:

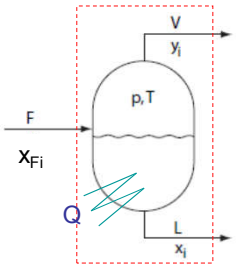


q-line / Feed-line:
•Feed sat. liquid (q=1): Vertical.
•Feed sat. vapor (q=0): Horizonta

Book: 11.7C

Given pressure

3. pT-Flash



- Need to find V/F first
- Write VLE as: $y_i = K_i x_i$
  - K_i is mainly a function of p and T, so can often be assumed constant for pT-flash
  - For example, ideal mixture, $K_i = p_i^{sat}(T)/p$
- Combine mass balance and VLE:
  - $Fx_{Fi} = Lx_i + VK_ix_i$
  - Solve for x_i:
    - $x_i = Fx_{Fi} / (F-V+VK_i)$ or $x_i = x_{Fi} / [1 + V/F(K_i-1)]$
  - Need to find V/F…(iterative solution = «trial and error»)
    - Book 11.7C-3: Use $\Sigma x_i = 1$.
    - Often better: Use $\Sigma y_i - \Sigma x_i = 0$ -> Rachford-Rice equation to get convex function in V/F::

$$\Sigma_i \frac{x_{Fi}(K_i-1)}{1+\frac{V}{F}(K_i-1)} = \frac{x_{F1}(K_1-1)}{1+\frac{V}{F}(K_1-1)} + \frac{x_{F2}(K_2-1)}{1+\frac{V}{F}(K_2-1)} + \cdots = 0$$

Given pressure

3. Example pT-flash: Iterative solution

Problem.
Feed: $F = 1$ mol/s. 40 mole-% propane (1), 10 % pentane (2), 50% hexane (3).
Flash at $T = 350$ K and $p = 10$ bar.
VLE data: Vapor pressures at 350K: 27.92 bar (1), 3.391 bar (2), 1.299 bar (3).

Solution:
K-values ($K_i = p_i^{\text{sat}}/p$): $K_1 = 2.792, K_2 = 0.3391, K_3 = 0.1299$.

Find V/F from Rachford-Rice by iteration. Want: LHS = 0.

1. First try: V/F=0.

   $\text{LHS} = \Sigma_i \frac{x_{Fi}(K_i-1)}{1+\frac{V}{F}(K_i-1)} = 0.4 \cdot 1.792 + 0.1 \cdot (-0.661) + 0.5 \cdot (-0.870) = 0.2158$

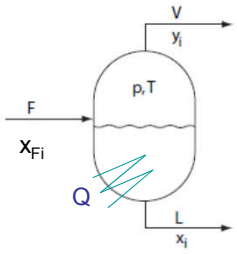
2. Second try: $V/F = 0.1$

   $\text{LHS} = \frac{0.4 \cdot 1.792}{1+0.1 \cdot 1.792} + \frac{0.1 \cdot (-0.661)}{1+0.1 \cdot (-0.661)} + \frac{0.5 \cdot (-0.870)}{1+0.1 \cdot (-0.870)} = 0.0607$

3. Further "trial and error" gives finally $V/F = 0.1436$:

   $\text{LHS} = \frac{0.4 \cdot 1.792}{1+0.1436 \cdot 1.792} + \frac{0.1 \cdot (-0.661)}{1+0.1436 \cdot (-0.661)} + \frac{0.5 \cdot (-0.870)}{1+0.1436 \cdot (-0.870)} = 0$

With $V/F = 0.1436$ we then find:
Liquid composition: $x_i = \frac{x_{Fi}}{1+\frac{V}{F}(K_i-1)}$: $x_1 = 0.318, x_2 = 0.111, x_3 = 0.571$
Vapor composition: $y_i = K_i x_i$: $y_1 = 0.888, y_2 = 0.038, y_3 = 0.074$

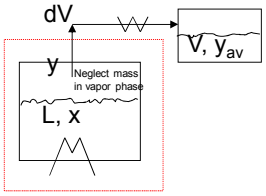


Example from:
S. Skogestad,
Prosessteknikk, 3. utgave,
Tapir, 2009, page 57

Single-stage batch distillation = Differential flash (Dynamic!)

- Ch. 11.3D (see also exercise)
  - L = amount of liquid in still [mol]
  - V = amount of vapor product [mol]
- Over short time dt: Evaporate amount dV
- Balance over still for short time dt:
  - Acc = In – Out
    Total: dL = 0 - dV [mol]
    Component: d(x L) = 0 - y dV [mol A]
- Get
  x dL + L dx = y dL
  L dx = (y-x) dL
  dx/(y-x) = dL/L

  Integrate: Get Rayleigh equation: $\int_{L_0}^{L_1} \frac{dL}{L} = \ln \frac{L_1}{L_0} = \int_{x_0}^{x_1} \frac{dx}{y-x}$ (y=f(x) from VLE)



- Comments:
  1. Multistage batch distillation with reflux is common in industry – see lab. exercise
  2. Single–stage batch distillation is more "efficient" than (continuous steady-state) flash. For example, need to vaporize less (smaller V/F) for a given separation. See Exercise.
- Steam distillation (usually for separating organic components):
  - Add water (nonsoluble) to feed mixture
  - Water makes separate liquid phase
  - Get low temperature (similar to vacuum distillation) because water reduces partial pressure

- Solution:
- **Question 1.** 1 liter coke contains n=5g / 44g/mol = 0.114 mol C02
- Assuming ideal gas this corresponds to (at 298K and 1 bar): V = nRT/p = 0.114*8.31*298/1.e5 = 0.028 m3 = 2.8 liter
- **Question 2.**
- xco2 = mole fraction CO2 in liquid
- From data (0.5 wt% CO2): xco2 = 0.5g/44 g/mol / (95g/18 g/mol + 5g/44 g/mol) = 0.0021
- Partial pressure of CO2 from Henry's law: pco2 = xco2*Hco2 = 0.0021 * 1670 bar = 3.5 bar
- Partial pressure of H2O from Raoults's law: ph2o = xh2o*psat(h20) = +0.998*0.03bar = 0.03 bar
- Total pressure, p = pco2 + ph2o = 3.5 bar + 0.03 bar = 3.53 bar
  - google: Typical filling pressure for CO2 is about 8 bar (but equlibrium is not reached)