Stripping

Maurizio Fermeglia

Maurizio.fermeglia@units.it

Department of Engineering & Architecture

University of Trieste

Agenda

- Stripping and steam stripping
- Material balances
- Equilibrium curve and operating lines
- McCabe Thiele plot
- Kremse-Brown-Souders equation
- Degrees of freedom
- Energy balances and adiabatic process
- Stripping: single stage process
- Integration of absorption with stripping processes
- Equipment for stripping (and absorption) processes

Stripping fundamentals

- Stripping is the operation that allows to **separate one or more volatile component from a liquid feed** when they are much more volatile than the other components in the feed.

- It is **a partial vaporization process**, which is carried out by contacting the liquid mixture with and extra gaseous phase (such as air, nitrogen, supersaturated steam), able to strip the volatile components.

  - In this way, stripping may be an alternative to a flash process, which is simpler but could not achieve the design specifications.

- Stripping requires a **second step** where the stripped components are separated from the stripping gas.

- The goal of a stripping process may be either **the recovery of a volatile product** of interest, or the **purification of a non-volatile liquid** from unwanted volatile substances.

Stripping and steam stripping fundamentals

- ◆ The separation of an outlet gaseous stripping stream to recover the volatile components is an important issue,
  - ▪ because upon condensation with regular cooling water a complete separation of the stripped components cannot be obtained,
- ◆ **The use of steam instead of non-condensable gases can be a good solution**,
  - ▪ as long as it can be condensed in a separate liquid phase with respect to the volatile components.
  - ▪ If, as often happens, the stripped components are insoluble in water, two liquid phases are obtained from the condenser, which can be easily separated by gravitational methods
  - ▪ **Steam stripping is the best option**.
- ◆ However, it has to be clear that steam must not condense within the column,
  - ▪ Column temperature should be larger than the boiling temperature at the operating pressure everywhere in the column.
- ◆ For the reasons above, in the following we will develop stripping processes with special attention to steam stripping.

Stripping: equilibrium curve and operating line

◆ A countercurrent **multi-stages stripping column** is commonly used for stripping processes.

◆ It is usually assumed that only a few components (let's say just one, component B) is transferred from the liquid to the vapor phase. **In stripping, the total L and V flow rates are larger at the top**.

◆ Similarly to absorption, the non-volatile component in the liquid stream as well as the steam in the vapor stream are considered as "**inert**" as they do not participate to the mass transfer.

Stripping: equilibrium curve and operating line

- Due to the non constant molar flow rates in the column, (like for absorption) also for stripping it is convenient to write mass and energy balances with respect to **inert flow rates** (which are constant) rather than to total ones, and to **composition ratios** rather than to composition fractions.
  - Similarly to the absorption process, **referring to inert** rather than to total flow rates allows the **operating lines to be linear equations**.
- Like in absorption, also for stripping the equilibrium relationship, which would be linear in a molar fraction reference, appears as the branch of a hyperbole using molar ratios:

$$Y = \frac{mX}{1 + (1 - m)X} = \frac{H_B X}{P + (P - H_B)X}$$
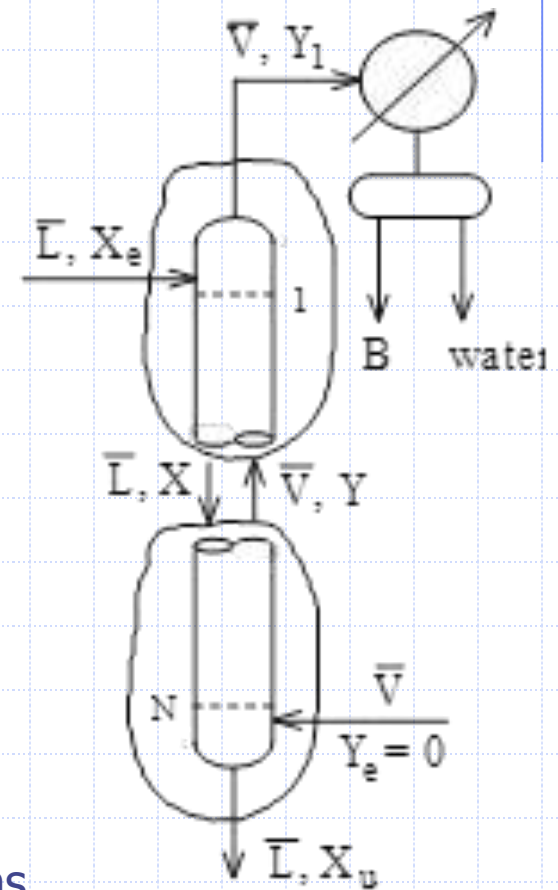
Stripping: material balances

◆ Three **material balances** are written for component B: (i) overall, (ii) with respect to the top of the column, and (iii) to the bottom of the column:

$$\bar{L}(X_e - X_u) = \bar{V}Y_u = \bar{V}Y_1$$

$$\bar{L}(X_e - X_j) = \bar{V}(Y_u - Y_{j+1})$$

$$\bar{L}(X_j - X_u) = \bar{V}Y_{j+1}$$

◆ Balances above refer to a tray column.

◆ However, they can be written also for a packed column

 ▪ In this case they are referred to bulk compositions of the column section considered

Stripping: material balances

- In the X-Y plane, the mass balance (referred either to the top or to the bottom) represents a straight line, whose slope is $\bar{L}/\bar{V}$.

- This is the reciprocal of the specific steam consumption, which can be expressed as:

$$\frac{\bar{V}}{\bar{L}} = \frac{(X_e - X_u)}{Y_u}$$

- In each section of the **column the composition of the vapor must be less than that of equilibrium with the liquid**,
  - because the mass transfer of B is from the liquid to the vapor phase.

- This is typical of stripping processes, similarly to distillation processes.

- It follows that **stripping is favored by high temperature and low pressure.**
  - In practice, atmospheric pressure is used, whereas the temperature is the one needed to avoid steam condensation within the column (i.e. not less than 120°C).
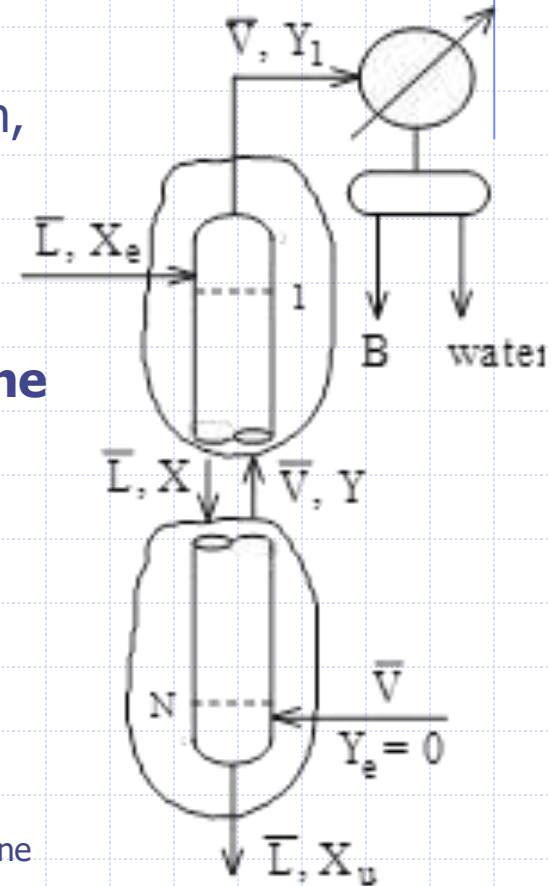
Stripping: equilibrium curve and operating line

◆ Calculation of the number of ideal stages needed to lower the liquid concentration from X_e to X_u

◆ The maximum slope of the operating line $(L/V)_{max}$, corresponding to the minimum steam consumption $(V/L)_{min}$ is estimated (figure) by the tangency condition of the operating line to the equilibrium curve (pinch point).

- However, the value of $(L/V)_{max}$, may not correspond to the tangency condition, as occurs when $X_e < X_{tan}$.

- In this case, the limiting condition is identified by the line passing by $(X_u, 0)$ and the intersection of the vertical line $X = X_e$ with the equilibrium curve.

$P, T = cost$

$Y_{1, max}$

Y_1

Y

L/V

X_{tan}

$(\bar{L}/\bar{V})_{max}$

X_u

X →

X_e
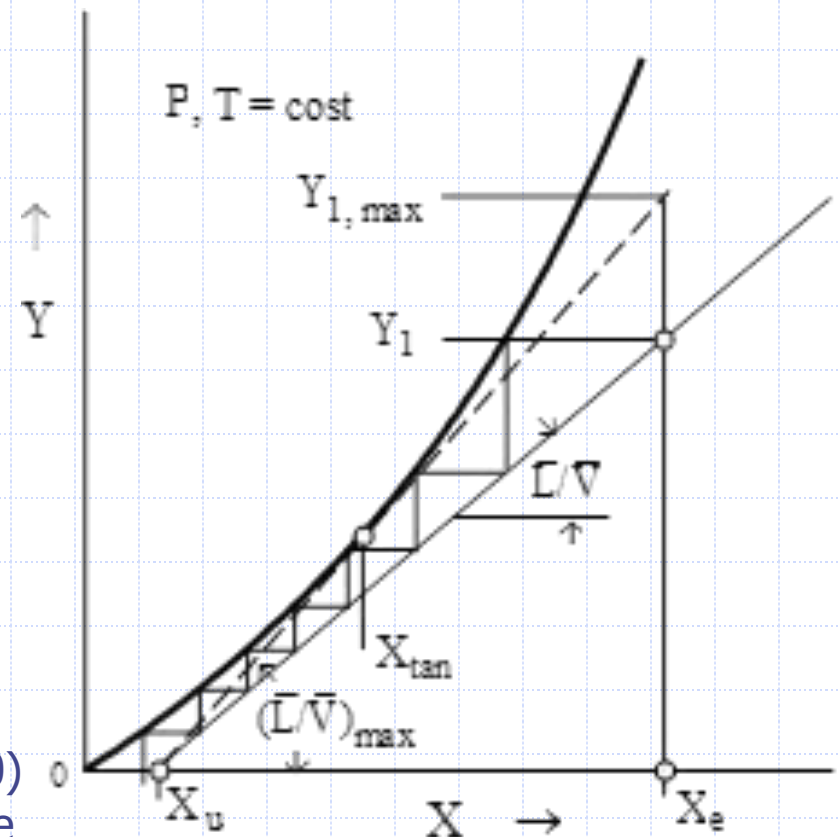
McCabe-Thiele Plot – Stripper
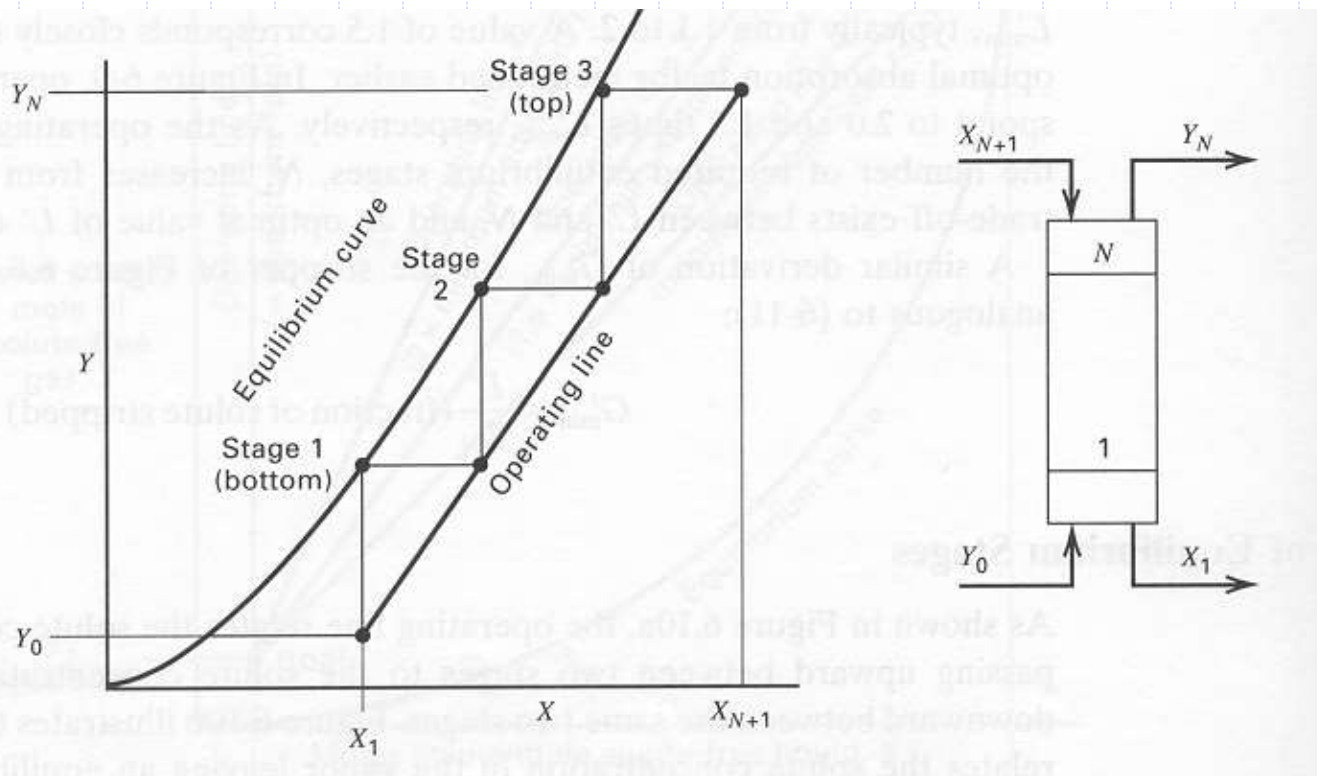
Stripping: the Kremse-Brown-Souders equation

♦ Only in the case of high stripping, the dilution of the component in the phases is such that it is possible
  - to substitute the molar ratios with the molar fractions,
  - the inert flows with the total ones.
  - Under these conditions, the analytical evaluation of the number of theoretical stages is possible, according to the procedure described for absorption.

♦ Material balance around ideal stage j reads:

$$L(x_j - x_{j-1}) = V(y_{j+1} - y_j)$$

♦ which can be rewritten as:

$$\frac{x_{j-1} - x_j}{x_j - x_{j+1}} = \frac{mV}{L}$$

♦ Considering the equilibrium relation $y_j = m \, x_j$ and multiplying member-by-member all the stage balances we get:

$$\frac{x_e - x_1}{x_u - y_e/m} = \left(\frac{mV}{L}\right)^{NP}$$

Stripping: the Kremse-Brown-Souders equation

◆ Finally, we obtain:

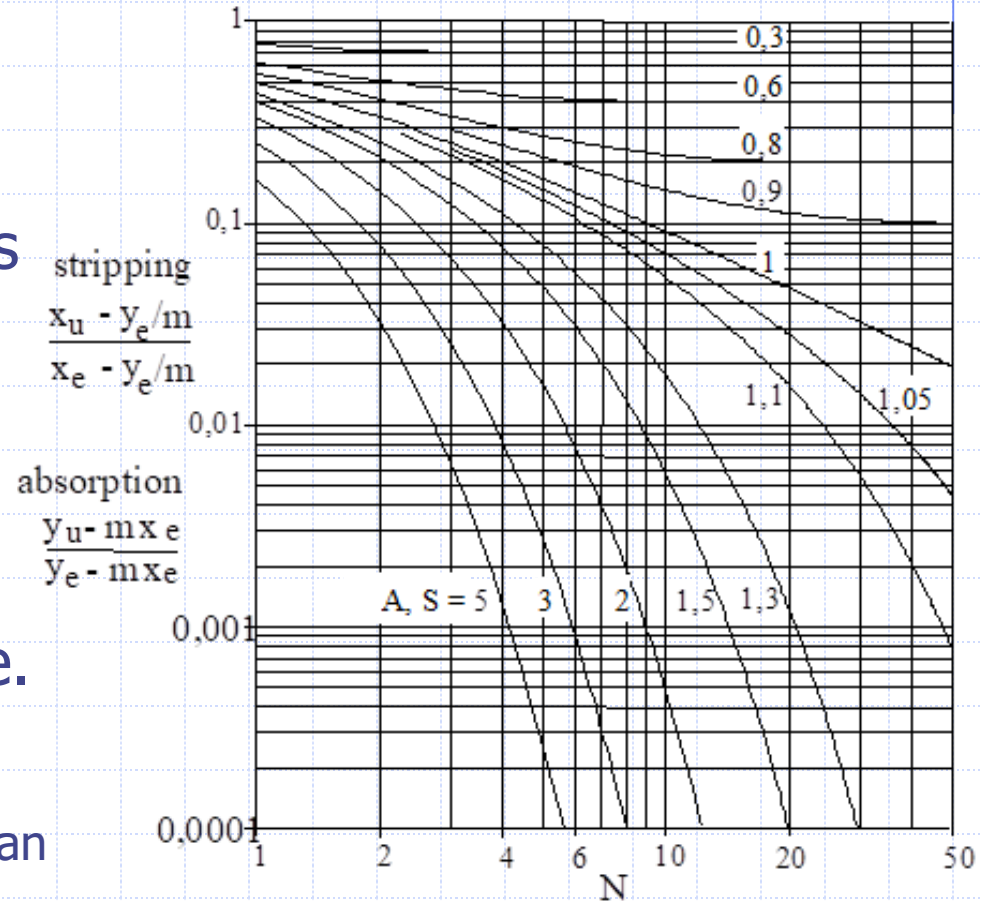$$\left(\frac{mV}{L}\right)^{NP} = \frac{x_e - x_u}{x_u - y_e/m}\left(1 - \frac{L}{mV}\right) + 1$$

◆ or:

$$\frac{x_e - x_u}{x_e - y_e/m} = \frac{S^{N+1} - S}{S^{N+1} - 1}$$

◆ where stripping factor S is defined as the inverse of the absorption factor:

$$S = \frac{mV}{L} = \frac{1}{A}$$

◆ Kremser-Brown-Souders eq. is plotted in the figure.

  ■ No solution to the stripping problem of interest can be found for recoveries higher than 90% if the stripping factor is lower than 0.9.

stripping

$$\frac{x_u - y_e/m}{x_e - y_e/m}$$

absorption

$$\frac{y_u - m x_e}{y_e - m x_e}$$

Final Notes on Strippers

- We use the **same assumptions and mole ratio methods** that we used for absorbers.
  - The OL will be the same as that used for absorbers.
- The difference, compared to an absorber, is that the **equilibrium curve will be above the operating line**.
  - This is analogous to the stripping section of a distillation column.
- Just as we stepped up from the bottom of a distillation column's stripping section, we **step up from the bottom** of the stripper.
  - Thus, one uses the same McCabe-Thiele algorithm method that we used for stepping up in distillation.
- In the algorithm,
  - the equilibrium relationship is expressed as $Y_{Eq} = Y_{Eq}(X_{Eq})$,
  - and the operating line is expressed in the form $Y_{OL} = X_{OL}(Y_{OL})$.
- Apart from these issues, the design approach for strippers is the same as that for absorbers.

Stripping: number of degrees of freedom

◆ Considerations developed for the absorption process can be repeated for stripping as well:

$$N_i = 2n + 2c + 5$$

◆ Usually, the values of **n thermal dispersions** are known, and those of **n pressures** must be assigned, as well as **C + 2 variables of the two feeds** are set, so that only 1 degree of freedom remains.

◆ This is an uncomfortable situation, leading to no degrees of freedom in rating problems.

◆ So, it is decided to **increase this number by 1**, considering the inlet steam flow rate as the second degree of freedom.

◆ So, a **stripping column has two degrees of freedom in process design** (for instance X_u and V) **and one in process rating** (for instance X_u).

Stripping: selection of degrees of freedom

◈ In design mode:

- ■ When designing a continuous counter-current stripping process, X_u is usually the design specification.

- ■ When **designing** a continuous counter-current stripping process, the flow rate of the stripping steam is usually kept as lowest as possible, to reduce energy duty costs. In general, the optimum value ($\underline{V}_{opt}$) can be related to the one of ($\underline{V}_{min}$) → ($\underline{V}_{opt}$) = K ($\underline{V}_{min}$)

◈ In rating mode:

- ■ In the case of rating, the **only available degree of freedom** is set on X_u, which is again the design specification, and the steam flow rate is the one resulting from calculation without the possibility to optimize it.

Stripping: overall energy balance

◆ Simplified overall energy balance for an adiabatic absorption column:

$$\lambda_B \bar{L}(X_e - X_u) = \bar{L} \, C_p^L \big(T_e^L - T_u^L\big) + \bar{V} \, C_p^V \big(T_e^V - T_u^V\big)$$

- remember that $\bar{L}(X_e - X_u) = \bar{V} \, Y_u$

◆ This energy balance is written **on a molar basis**,

- so that the specific heat of condensation and the specific heat capacities of both the vapor and the liquid are in molar basis as well.

◆ If we account for real property values and real flow rates, we can see that only the first term in the right hand side contributes to the calculation of temperatures.

- Therefore, it is reasonable to simplify the previous equation into:

$$\lambda_B (X_e - X_u) = C_p^L \big(T_e^L - T_u^L\big)$$

◆ It is concluded that the vaporization of component B takes place at the expenses of the sensible heat of the liquid, which then cools from the top to the bottom: **in a stripping column the temperature decreases from the top to the bottom.**

Stripping: calculation of the adiabatic process

◆ Starting form the top of the column (tray no. 1):
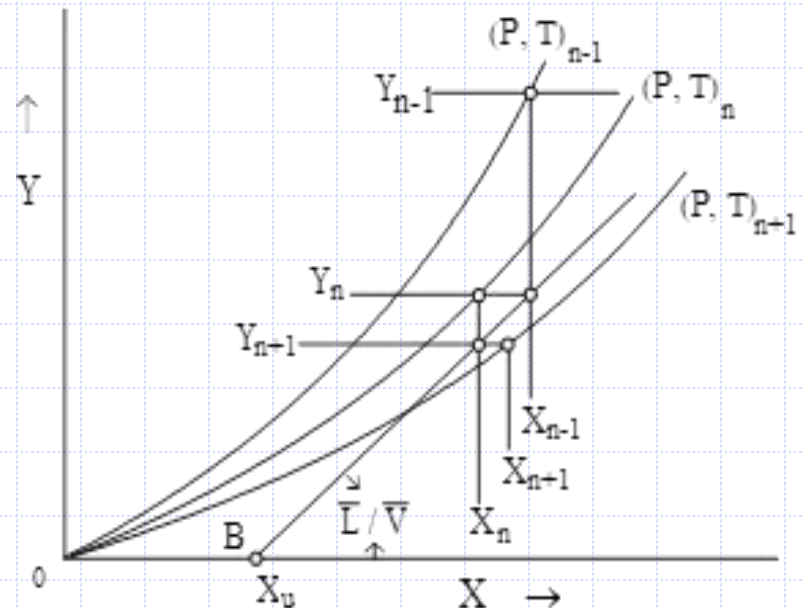
$$\lambda_B(X_e - X_1) = C_p^L(T_e^L - T_1^L)$$

- From

$$Y = \frac{H_B X}{P + (P - H_B)X}$$

- One gets

$$X_1 = \frac{PY_1}{H_B(T_1)(1 + Y_u) - PY_u}$$
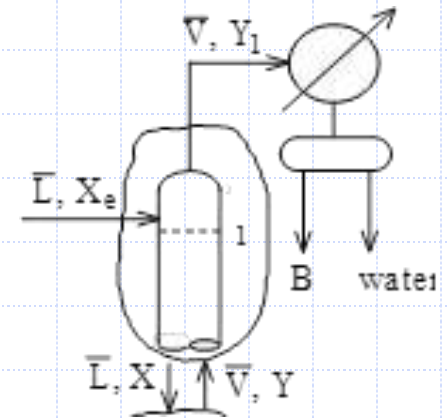
◆ X_1 and T_1 can be calculated by an iterative procedure.

◆ Then Y_2 results from:

$$\bar{L}(X_e - X_1) = \bar{V}(Y_u - Y_2)$$

◆ Stage by stage calculation is performed until $X_j < X_u$.

# Stripping: calculation of the adiabatic process

◆ Alternately, but less rigorously, one can calculate the "adiabatic" equilibrium curve.

- The range between X_e and X_u is divided into a number of segments.
- Then, from each X_k, the corresponding temperature T_k is calculated:

$$\lambda_B (X_e - X_k) = C_p^L (T_e^L - T_k^L)$$

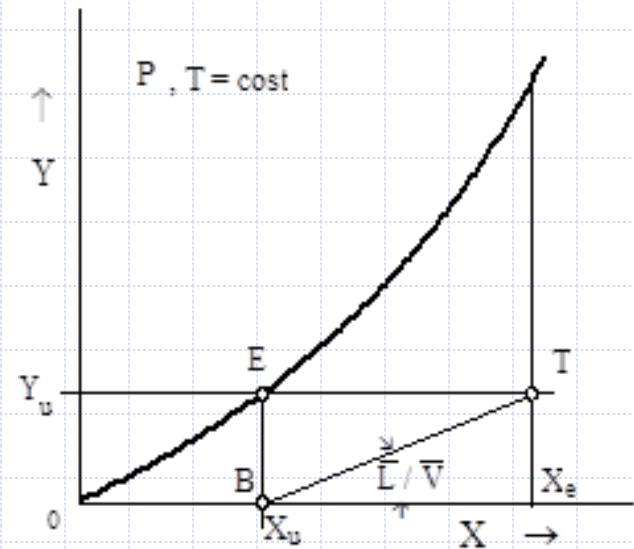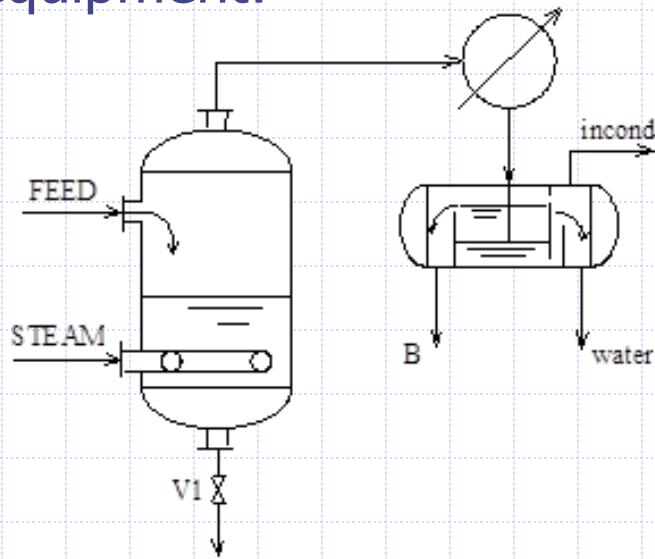◆ The value of Y_k is calculated from the equilibrium relation

$$Y_k = \frac{H_B X_k}{P + (P - H_B) X_k}$$

- It is observed that the curve is parametric in the conditions of the liquid feed.

◆ Minimum steam consumption and number of stages are evaluated as in the isothermal case

$T_e = 130°C$
$X_e = 0,15$

isotherm T_e

X_{tan}
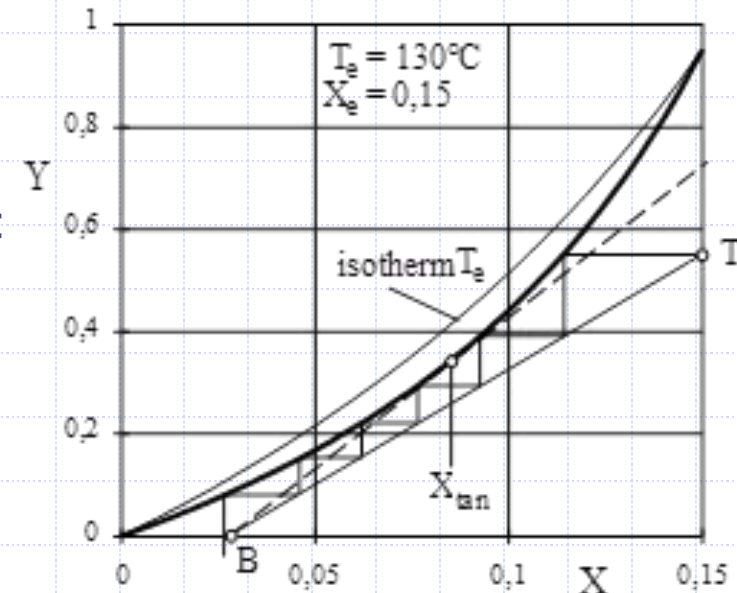
Stripping: calculation of a single stage process

◆ The equipment:

◆ **Continuous process**: specific steam consumption is given by:

$$\frac{\bar{V}}{\bar{L}} = \frac{(X_e - X_u)}{Y_u^*}$$

$$\frac{\bar{V}}{\bar{L}(X_e - X_u)} = \frac{1}{Y_u^*} = \frac{P}{H_B X_u} + \frac{P - H_B}{H_B}$$

$$Y_u^* = \frac{H_B(T_u) X_u}{P + (P - H_B(T_u)) X_u}$$

Stripping: calculation of a single stage process

- ◈ **Semi-batch process** (same piece of equipment):
  - It is interesting to consider also a semi-batch single-stage stripping process, and to compare it with the corresponding continuous operation described just above.
  - In this case the liquid feed is loaded at the beginning, and valve V_1 is kept closed till the end of the operation.

- ◈ A differential material balance is written:

$$Y d\tilde{V} = -d(\tilde{L}X) = -\tilde{L}dX$$

- ◈ which can be integrated to calculate the specific steam consumption:

$$\frac{\tilde{V}}{\tilde{L}} = \frac{P}{H_B} \ln \frac{X_{in}}{X_{fin}} + \frac{P - H_B}{H_B} \left(X_{in} - X_{fin} \right)$$
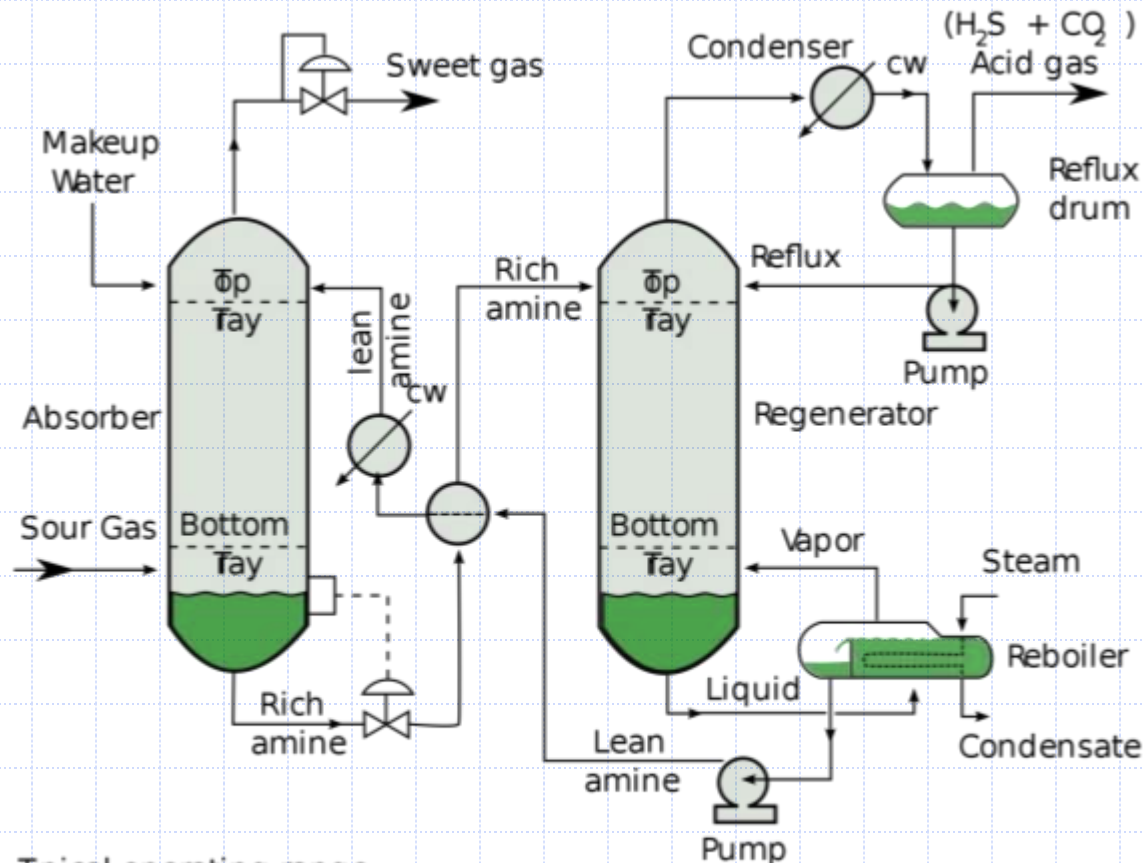
- ◈ The same steam duty can be expressed in terms of unit of product B:

$$\frac{\tilde{V}}{\tilde{L}(X_{in} - X_{fin})} = \frac{P}{H_B} \frac{\ln \dfrac{X_{in}}{X_{fin}}}{X_{in} - X_{fin}} + \frac{P - H_B}{H_B}$$

  - (compare it with continuous process)

Integration of Absorption and Stripping processes
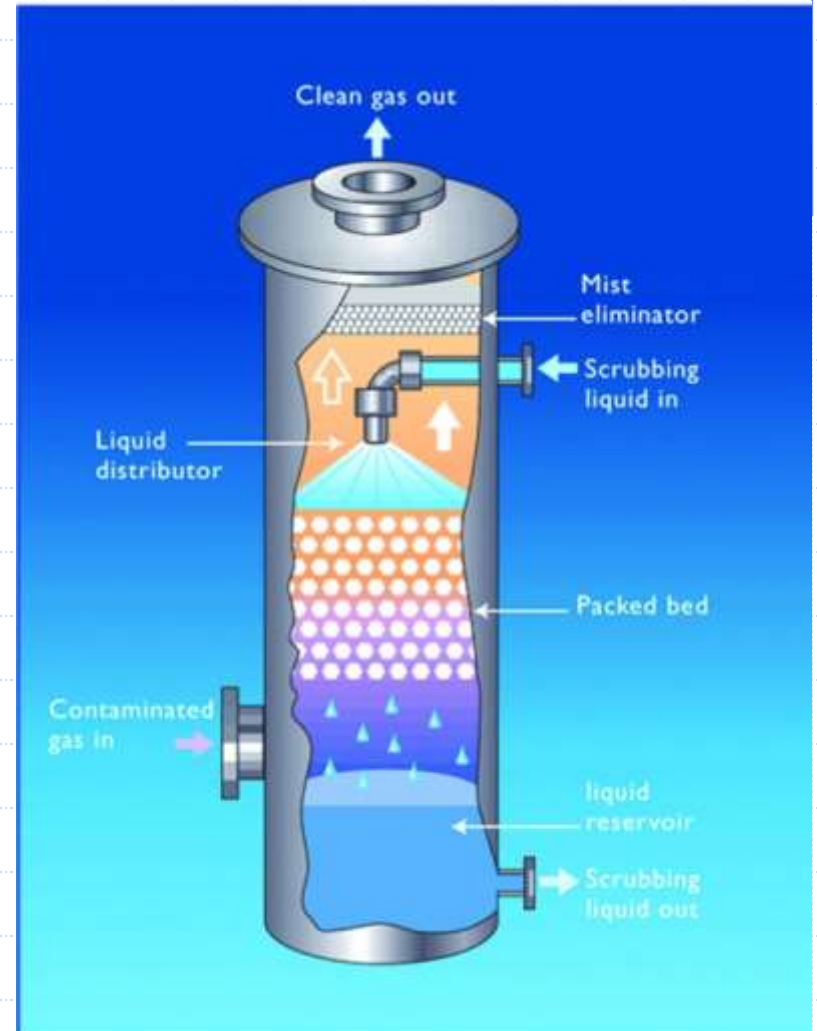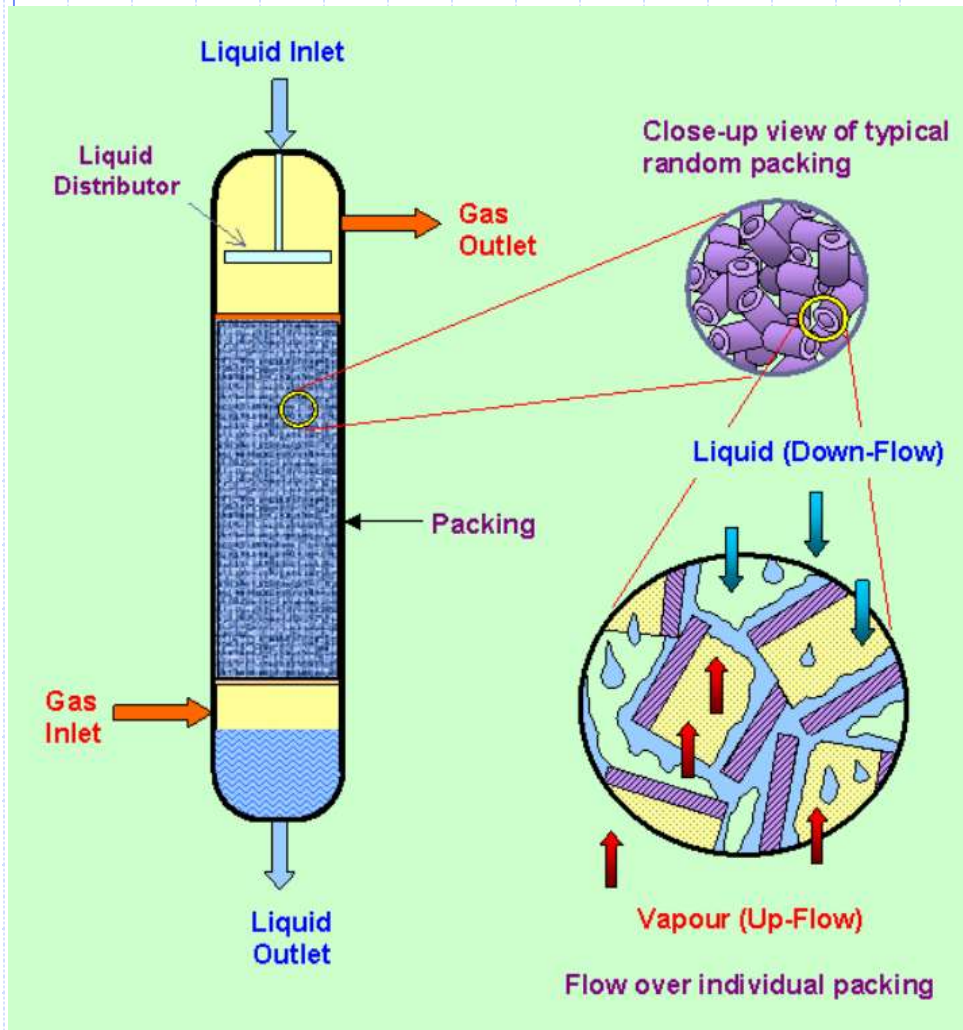
◆ A typical amine gas treating process

Typical operating range

absorder : 35 to 50°c and 5 to 205 atm of absolute pressure
Regenerator : 115 to 126°c and 1.4 to 1.7 atm of absolute pressure
at tower bottom

Integrated Absorption and Stripping for CO$_2$ capture

- MEA carbon capture process flowsheet within Aspen Plus

Striping and absorption equipment

Striping and absorption equipment

Gas (vapor) out

Liquid in

manhole

distributor

structured pck

Liquid in (possible)

support grid

manhole

Random pck

support grid

Gas (vapor) in
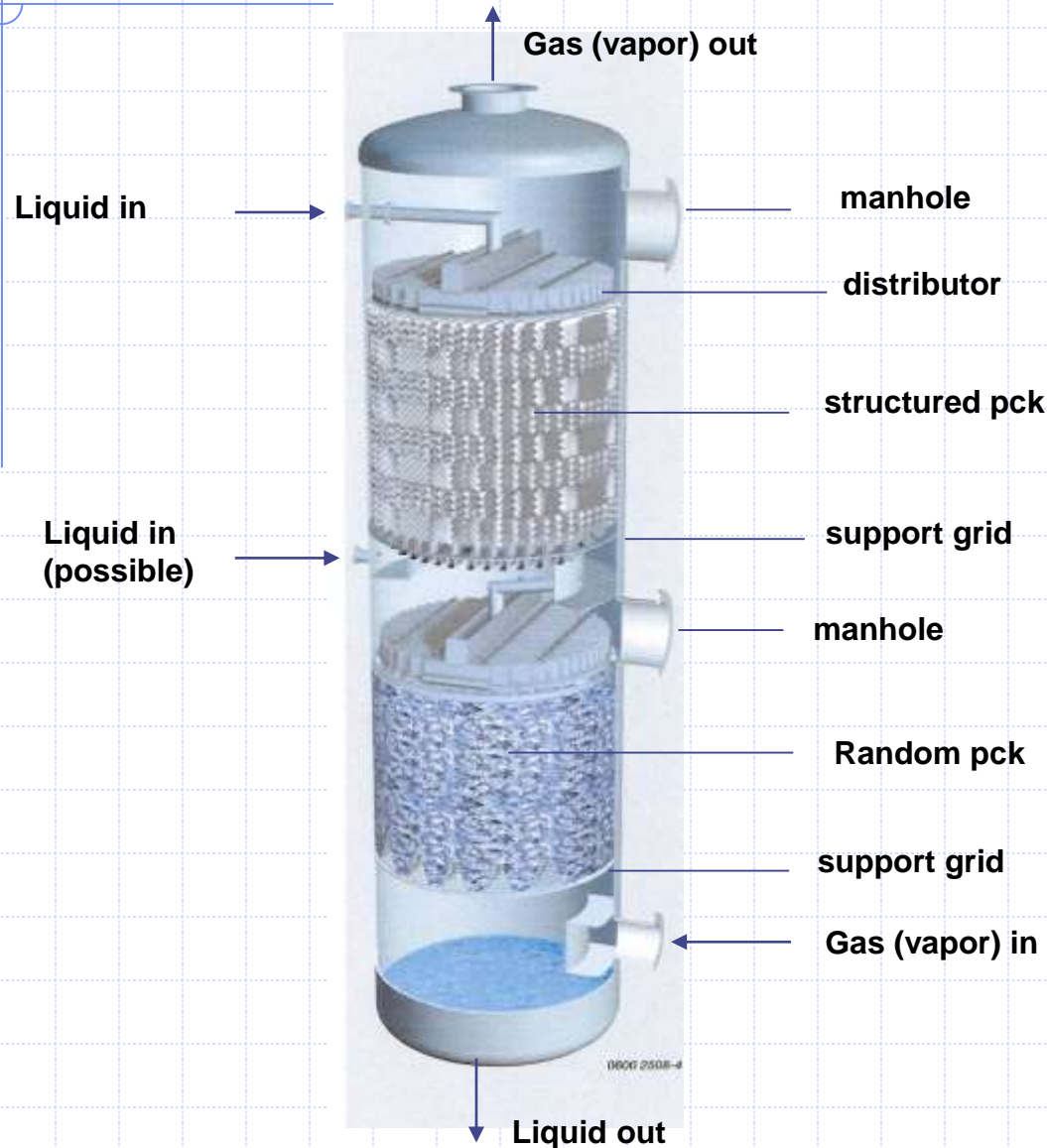
form Sulzer manual

Liquid out

Temperature and pressure effects

◆ **Why low pressure?** $\quad P y_2 = x_2 H_2$

- Because a decrease in pressure (P) is accompanied by a decrease in solubility of gas (x_2) in the liquid phase (Henry's Law).
- With decreasing pressure, the saturation temperature gets reduced, which would cause the entrainment of the less volatile component into the overheads.

◆ **Why high temperature?** $\quad P y_2 = x_2 H_2$

- Because at higher T, H increases reducing x_2 and raising the concentration of more volatile component into the gas phase.
- If T is too high (above the dew point of the mixture), it would lead to entrainment of the less volatile component into the overhead and increase the condenser duty.

◆ **Low P and high T facilitates better stripping.**

- Reducing solubility of gas (x_2) in the liquid phase
- But there are limitations to both temperature and pressure conditions used in case of stripping operation.
- The ultimate trade-off is between your required product purity and minimizing reboiler and condenser duties.

Stripping with Radfrac

- ◆ Consider the absorption column used for separation of Acetone water gas mixture
  - The liquid feed to the stripper should be the liquid product from the absorber (case 4), but heat it to 85°C (at 1 atm) before feed it to the stripper.
  - The gas feed to the stripper should be pure steam, at 1 atm.
  - Use 6 stages. Be sure to put your steam (the stripping gas) on stage 6 and the liquid from the absorber above stage 1.
  - Stripper is at 1.0 atm.
- ◆ Specification: liquid leaving stripper acetone mole fraction $< 1.0 \, E - 04$
- ◆ Case 1:
  - Set the steam flow rate at 20 kmol/h. The steam should be superheated to 101°C.
  - Does this design satisfy the spec? (It should)
  - What is the acetone mole frac in the gas leaving the stripper? Note that this is high enough that pure acetone could be recovered by distillation.
- ◆ Case 2:
  - Repeat with saturated steam at 1 atm and 100°C (set $V/F = 1.0$).
- ◆ Case 3:
  - Using saturated steam ($V/F = 1$) at 1 atm, reduce the steam flow rate to just satisfy the specification on the outlet liquid composition (sensitivity analysis).
- ◆ Case 4:
  - Reduce the pressure of the stripper and the steam to 0.5 bar with steam at $V/F=1$ and 15 kmol/h .
  - What can you conclude about the effect of pressure?

Complete gas plant (absorption + stripper)

- ◆ Design a complete gas plant to process the feed of acetone water gas mixture.
    - ▪ Gas temperature is 10°C. Absorber has 6 stages, pressure = 2.0 atm.
    - ▪ The outlet mole frac of acetone leaving in the gas should be less than 0.003 mole frac.
    - ▪ The solvent fed to the absorber is pure water at 10°C and 2.0 atm.
    - ▪ Flow rate is 100 kmol/h. The liquid outlet from the absorber should be heated to 70°C at 0.5 atm and then be sent directly to a stripper (N= 6) operating at 0.5 atm with a gas feed of 0.5 atm saturated (V/F = 1) steam. The acetone mole frac leaving in the liquid from the stripper should be less than 0.0001.

- ◆ Adjust the steam flow rate until your outlet is slightly below this value.
    - ▪ If the outlet gas specification is not met, adjust operating conditions (L, T, N, or P) until it is met.