Chemical unit operations 2.

lectures  2 hours/week
calculation seminars weekly 1 hours
laboratory weekly  3 hours
Requirements

• Attendance will be checked.
• Requirements for the signature:
  – Attending on minimum 66% of the lectures and calculation seminars, and on all laboratory practices is required.
  – One calculation test will be scheduled during the semester. Exact dates and topics covered will be announced later. The calculation test have to be passed for signature. The grade of the calculation test counts as 25% of the final grade.
  – Nine laboratory measurements will be scheduled. Each measurement have to be performed, and reports accepted.
• Students having valid signature may take a written exam during the examination period. Application for the exams is only possible via the Neptun system.
• Website of the course: http://kkft.bme.hu/oktatas/cuo2/
Please check it frequently!
Distillation

Edit Székely, Béla Simándi
Topics to be covered

• Distillation in the industry (introduction).
• Batch distillation.
• Flash distillation.
• Distillation columns = rectification.
Distillation in the industry

• Ethanol production
  – Food industry
  – Chemical industry
  – Bioethanol
Distillation in the industry

- Ethanol production
- Oil industry
  - fractionation

(products based on distillation intermediates: fuels, raw material of chemical industry, plastics, solvents, bitumen etc.)
Distillation in the industry

- Ethanol production
- Oil industry
- Waste water treatment
  - Mainly waste waters with high solvent contamination
  - Waters from absorption (purification of exhaust gases).
Advantages of distillation

• Major separation process for homogeneous liquids of two or more components.
• Separation is based on the difference in boiling points (volatility).
• No additional chemicals are needed, but energy requirement is relatively high.
• In a large number of separation task it is the most economical option.
Boiling point

• Depends on:
  – ingredients
    • molar ratios, exact composition
  – pressure

A liquid starts to boil if the sum of the partial pressure of its ingredients is equal to the pressure of the environment.
Vapour pressure of a pure component

• Vapour pressure is the pressure measured above a neat liquid component in equilibria (no other components in the system).

• It depends on the materials itself, and on temperature. Always increases with temperature.

• Antione equation:

\[ \lg p^0 = A - \frac{B}{C + T} \]

- \( P^0 \) vapour pressure (Pa; Hgmm),
- \( T \) temperature (°C, K),
- \( A, B, C \) Antionie-constants
Volatility

- If its boiling point is lower at a chosen pressure than the other’s one, that component is called more volatile.
- If a liquid mixture is boiling, in general, the more volatile component has a higher relative concentration in the vapour phase than in the liquid phase.
- Volatility is the ratio of the molar fraction of component $j$ in the vapour phase over its molar fraction in the liquid phase.

$$K_j = \frac{y_j}{x_j}$$
Laws of Raoult and Dalton

**Dalton’s law**

*Partial pressure is the share of the given vapour of the total pressure. This is proportional with its molar fraction in the vapour phase.*

\[ p_j = y_j P \]

- \( p_j \) partial pressure of component \( j \) (Pa),
- \( y_j \) molar fraction of component \( j \) in vapour phase (-),
- \( P \) total pressure (Pa).

**Raoult’s law**

*A mixture is ideal from a practical point of view if law of Raoult is valid for any compositions in the examined range of temperatures.*

\[ p_j = p^0_j x_j \]

- \( p^0_j \) vapour pressure of neat component \( j \) (Pa) at the given temperature,
- \( x_j \) molar fraction of component \( j \) in the liquid phase.
Bubble point – dew point diagrams

- These diagrams are constructed based on experimental data obtained in special equipment.
Measurement of vapour-liquid equilibrium data

- The liquid is heated by electrical heating and kept continuous boiling. Pressure is strictly kept constant.
- The vapour phase is circulated.
- At equilibrium samples are taken from both phases, and composition is analysed.
Bubble point – dew point diagrams

• These diagrams are constructed based on experimental data obtained in special equipment.

• In case of ideal mixtures, phase diagrams can be easily obtained by simple calculations.

• A mixture is ideal if:
  – Law of Raoult is valid,
  – Complete miscibility in liquid phase,
  – The constituents are usually chemically similar (e.g. linear chain hydrocarbons).
Bubble point – dew point curves and the equilibrium curve

mixture of benzene and toluene at atmospheric pressure \((P=1.013 \text{ bar})\)
Bubble point – dew point curves and the equilibrium curve

$mixture$ of isopropil-ether–isopropanol at atmospheric pressure
Bubble point – dew point curves and the equilibrium curve

$mixture$ of acetone-chloroform at atmospheric pressure
Bubble point – dew point curves and the equilibrium curve

$mixture$ of ethyl acetate – water at atmospheric pressure
Batch distillation
Batch distillation – mathematical description of the unit operation

Deriving the Rayleigh-equation

Set up the molar balance and component balance equations for an infinitely short $\text{d}t$ time.

During this $\text{d}t$ time, a vapour of molar amount $dV$ is produced with a composition $y$ (molar increase of distillate is equal, since distillate is formed by condensing the vapour). Molar amount of the boiling liquid in the vessel is meanwhile decreased by $dL$.

Thus the molar balance is:
Rayleigh-equation

\[ dL = dV = dD \]

\[ L \cdot x = (L - dL)(x - dx) + dV \cdot y \]

\[ L \cdot x = L \cdot x - dL \cdot x - L \cdot dx + \]

\[ + dL \cdot dx + dV \cdot y \]

neglect second-order differential \( dLdx \) and reorder:

\[ 0 = -dL \cdot x - L \cdot dx + dV \cdot y \]

substitute \( dL = dV \)

\[ 0 = -dL \cdot x - L \cdot dx + dL \cdot y \]

separate the variables

\[ L \cdot dx = dL \cdot (y - x) \]

\[ \frac{dx}{y - x} = \frac{dL}{L} \]

\[ \int_{x_0}^{x_1} \frac{dx}{y - x} = \frac{L_0}{L_1} \int \frac{dL}{L} \]

\[ \int_{x_1}^{x_0} \frac{dx}{y - x} = \ln \frac{L_0}{L_1} \]
Batch distillation – mathematical description of the unit operation

Applications of the Rayleigh-equation

where

\[ \int_{x_0}^{x_1} \frac{d x}{y - x} = \ln \frac{L_0}{L_1} \]

\( y \) and \( x \) are compositions of vapour and liquid phases in equilibrium; 
index 0 refers to initial (at \( t_0 \) time) 1 refers to the final (\( t_1 \)) values; 
\( L \) is molar amount of the liquid phase (mol).

If initial amount of the liquid (\( L_0 \)) and its composition (\( x_0 \)) is known and the desired purity is defined (\( x_1 \)), amount of remaining liquid (\( L_1 \)) can be calculated by the Rayleigh-equation.
Batch distillation – mathematical description of the unit operation

Calculation of average composition in distillate

$L_0, L_1, x_0, x_1$ are already known.

From molar and composition balances the two unknown can be calculated.

\[
L_0 = L_1 + D \Rightarrow D = L_0 - L_1
\]

\[
L_0 \cdot x_0 = L_1 \cdot x_1 + D \cdot \bar{x}_D \Rightarrow \bar{x}_D = \frac{L_0 \cdot x_0 - L_1 \cdot x_1}{D}
\]

where $\bar{x}_D$ is the average composition of distillate.
Applications of batch distillation

• Limits of separation. Subsequent distillations are needed.

• When relatively smaller amount of feed have to be purified batch distillation is more economic than continuous distillation processes.

• When composition of feed changes frequently, but distillation have to be performed in the same unit.
Continuous single stage distillation / flash distillation

• Consists of:
  – vaporizing a definite fraction of the liquid in such a way, that the evolved vapor is in equilibrium with the residual liquid,
  – separation the vapour and the liquid,
  – condensing the vapour.

• It is a continuous, steady-state operation.
  – steady-state: temperature, pressure, compositions and flow rates are constant.

• Separation performed is equivalent to one single theoretical stage.
Continuous single stage distillation at constant pressure

Molar flow rate of feed is $F$. Its composition if $x_F$ (molar fraction of the more volatile component in case of binary mixtures).

Molar flow rate of the vapour is $V$. Its composition is $y$ (molar fraction of the more volatile component in case of binary mixtures). The vapour is in equilibrium with the liquid product.

Molar flow rate of liquid product is $L$. Its composition is $x$ (molar fraction of the more volatile component in case of binary mixtures).

Condensate of heating steam.

Heating steam.
Flash distillation by reduction of pressure

Liquid phase feed

Preheater. The liquid is heated below its boiling point at pressure $P_1$. The final temperature should be sufficiently higher than temperature of boiling at $P_2$.

Pressure reducing valve

Cyclone. Vapour and drops of liquid are separated by sedimentation.

Vapour

$L, x$

Liquid product

$F, x_F$

$p_1 > p_2$
Flash distillation by partial condensation

Vapour feed

Partial condensator

Vapour product

Cyclone. Vapour and drops of liquid are separated by sedimentation.

Liquid product

$F, x_F$

$V, y$

$L, x$
Flash distillation – mathematical description

Molar balance

\[ F = L + V \]

Component balance

\[ F \cdot x_F = L \cdot x + V \cdot y \]

Express \( y \) as function of \( x \) and plot the expression in the equilibrium diagram!

Since \( x \) and \( y \) are equilibrium compositions, intersection of the two curves is the point of operation.

\[
y = \frac{F \cdot x_F - L \cdot x}{V} = \frac{F}{V} x_F - \frac{F - V}{V} x = \frac{F}{V} x_F - \frac{L}{V} x
\]
Flash distillation

\[ y = -\frac{L}{V} x + \frac{F}{V} x_F \]

if \( x = x_F \)

\[ y = -\frac{L}{V} x_F + \frac{F}{V} x_F = x_F \]
Flash distillation – range of operation

Flash distillation is one single equilibrium stage.
Flash distillation - summary

• Rarely used as individual separation unit because its limitations in purity.
• In case of non-ideal mixtures like heteroazeotropic mixtures it might be an option.
• Partial reboiler of a rectification column is a flash distillation unit.
Distillation columns – continuous rectification

• A separation process performed in steady state operation.
• As usual for continuous processes, it is mostly applied at constant and high feed rates.
• Frequently used in industrial scale.
• Separation is based on vapour-liquid equilibrium.
Rectification = subsequent partial condensations and subsequent partial evaporations

\[ P = \text{constant} \]
Distillation column

- Column
  - Rectifying section, upper part of the column
  - Stripping section, lower part of the column
- Condenser
- Reboiler
- Feed, $F, x_F$
- Distillate, $D, x_D$
- Bottoms, $W, x_W$
Molar balance

\[ F = D + W \]

molar flow rate of feed \((F)\), of distillate (overhead product) \((D)\) and bottoms product \((W)\) (mol/s or kmol/h).

Component balance

\[ F \cdot x_F = D \cdot x_D + W \cdot x_W \]

Compositions: molar fraction values of the more volatile component.
Simple calculation methods for initial estimations

- The technique discussed is considered to be the simplest method for analysis of binary distillation.
- In an ideal stage (plate or tray), the V phase leaving the stage is in equilibrium with the L phase leaving the same stage.
- The problem is that of finding the number of ideal stages required in an actual column to achieve a desired separation.
- If the number of theoretical stages can be determined, and information on the stage efficiencies is available, the number of actual stages can be calculated.
Reflux ratio, operating lines

Reflux ratio:
\[ R = \frac{L}{D} \]

Basic assumption: constant molal overflow.
Continuous fractionation column- Constant molal overflow

Assumptions:
• The column is adiabatic (sufficient insulation, negligible heat loss).
• Heat effects (heats of solution, heat losses to and from column, etc.) are negligible.
• Heat of evaporation is the major source of any heat effects in the column.
• Molal heats of vaporization of the components are roughly the same. For every mole of vapour is condensed, a mole of liquid vaporized.

Results:
• Liquid and vapour molar flow rates are constant in the rectifying and in the stripping sections, separately.
Continuous fractionation column – reflux ratio, operating lines

Plates are numbered serially from the top down. Flows leaving the plates are numbered accordingly.

Assumption: liquid and molar flows leaving a theoretical (ideal) plate have equilibrium compositions.

Based on constant molal overflow:

\[ V_1 = V_2 = \ldots = V_n = V \]

\[ L_0 = L_1 = L_2 = \ldots = L_n = L \]
Rectifying operating line

Consider the part of the column enclosed by control line, a component balance of rectifying section can be written as:

\[ V \cdot y_{n+1} = L \cdot x_n + D \cdot x_D \]

Molar balance of the rectifying section (similar to the balance equation of the condenser):

\[ V = L + D \]

Expressing \( y_{n+1} \) from the component balance and substituting into molar balance equation we obtain:

\[ y_{n+1} = \frac{L}{V} \cdot x_n + \frac{D}{V} \cdot x_D = \frac{L}{L+D} \cdot x_n + \frac{D}{D+L} \cdot x_D \]
Rectifying operating line

\[
y_{n+1} = \frac{L}{V} \cdot x_n + \frac{D}{V} \cdot x_D = \frac{L}{L+D} \cdot x_n + \frac{D}{D+L} \cdot x_D
\]

Divide by \(D\) and substitute the reflux ratio \((R=L/D)\):

\[
y_{n+1} = \frac{R}{R+1} \cdot x_n + \frac{x_D}{R+1}
\]

Generalized form is an equation of a straight line:

\[
y = \frac{R}{R+1} \cdot x + \frac{x_D}{R+1}
\]
Operation line of the stripping section

Balance equations can be set analogously to the lower part of the column. Control line includes the still and all plates below plate $m$.

$V'$ and $L'$ are the molar flow rates of vapor and liquid in the stripping section:

$L' = V' + W$

$L' \cdot x_m = V' \cdot y_{m+1} + W \cdot x_W$
Operation line of the stripping section

\[ L' = V' + W \]

\[ L' \cdot x_m = V' \cdot y_{m+1} + W \cdot x_W \]

\[ y_{m+1} = \frac{L'}{V'} \cdot x_m - \frac{W}{V'} \cdot x_W \]

\[ y = \frac{L'}{V'} \cdot x - \frac{W}{V'} \cdot x_W \]
Continuous fractionation column – reflux ratio and operating lines

With known reflux ratio operating line of the rectifying section can be draw in the VLE (equilibrium) diagram.

The condition of the feed can be deduced by the slope of the feed line or q-line. The q-line is that drawn between the intersection of the operating lines, and where the feed composition lies on the diagonal line.

\[ y = \frac{L'}{V'} \cdot x - \frac{W}{V'} \cdot x_w \]
Continuous fractionation column – feed line / q-line

\[ q = \frac{H_F - h_F}{\lambda_F} \]

, where \( H_F \) is the enthalpy of the saturated vapour with the composition of \( x_F \) (J/mol), \( h_F \) is the enthalpy of the feed (J/mol), \( \lambda_F \) is molar heat of vaporization of a mixture with \( x_F \) composition (J/mol).

<table>
<thead>
<tr>
<th>Consistence and properties of feed</th>
<th>( h_F )</th>
<th>( q )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold liquid (below its boiling point) known as subcooled liquid</td>
<td>( h_F &lt; H_F - \lambda_F )</td>
<td>( 1 &lt; q )</td>
</tr>
<tr>
<td>Boiling liquid known as saturated liquid</td>
<td>( h_F = H_F - \lambda_F )</td>
<td>( q = 1 )</td>
</tr>
<tr>
<td>Mixture of liquid and vapour, ( q ) is equal to liquid mole fraction</td>
<td>( h_F = H_F - q \cdot \lambda_F )</td>
<td>( 0 &lt; q &lt; 1 )</td>
</tr>
<tr>
<td>Saturated vapour</td>
<td>( h_F = H_F )</td>
<td>( q = 0 )</td>
</tr>
<tr>
<td>Overheated (superheated) vapour</td>
<td>( h_F &gt; H_F )</td>
<td>( q &lt; 0 )</td>
</tr>
</tbody>
</table>
Continuous fractionation column – effect of feed condition on molar flow rates

Molar balance of the feed plate:

\[ V' + L + F = V + L' \]

When feed is mixture of vapour and liquid, \( q \) liquid fraction is added to the liquid and \( 1 - q \) fraction to the vapour flow.

\[ L' = L + q \cdot F \]
\[ V = V' + (1 - q) \cdot F \]
Continuous fractionation column – condition of feed

Deduct equation of rectifying operating line from equation of stripping operation line:

\[
y = \frac{L'}{V'} \cdot x - \frac{W}{V'} \cdot x_w \Rightarrow V' \cdot y = L' \cdot x - W \cdot x_w
\]

\[
y = \frac{L}{V} \cdot x_n + \frac{D}{V} \cdot x_D \Rightarrow V \cdot y = L \cdot x + D \cdot x_D
\]

\[
(V' - V) y = (L' - L) x - W x_w - D x_D
\]

\[
L' = L + q \cdot F
\]

\[
((q - 1) \cdot F) y = (q \cdot F) x - F \cdot x_F
\]

\[
V = V' + (1 - q) F
\]

\[
(q - 1) y = (q) x - x_F
\]

\[
y = \frac{q}{q-1} \cdot x - \frac{1}{q-1} \cdot x_F
\]

Knowing \(q\) the \(q\)-line can be drawn.
Effect of feed condition

\[
y \quad 1 \\
y_{D}=x_{D} \\
\]

Rectifying operation line

\[
tg\alpha = \frac{R}{R + 1} \\
0<q<1 \\
q=1 \\
q>1 \\
\]

Stripping operation line

\[
tg\alpha = \frac{q}{q - 1} \\
\]

Given:

R, q, x, x_{w}, x_{D}, x_{F}
Minimal reflux ratio

Given:
$q, x_w, x_D, x_F$

$R_{\text{min}} = ?$

$y_D = x_D$

$y_w = x_w$

$q$ line

$R_{\text{min}}$ can be calculated from the read value

$N = \infty$

$\tan \alpha = \frac{q}{q-1}$
Given:
- $x_w, x_D$
- $N_{\text{min}} = ?$

$N_{\text{min}} = 4$

Equilibrium curve

45° line: $x = y$
Simple calculation methods for initial estimations

• Calculation of the minimal number of theoretical plates.
  – gives us information about the difficulty of the desired separation,
  – needed: desired compositions of overhead and bottoms products.

• Minimal reflux ratio: to achieve the desired separation, reflux ratio has a minimal value.

• Number of theoretical plates is determined: with McCabe – Thiele method.
McCabe-Thiele method (1925)

\[ \tan \alpha = \frac{R}{R + 1} \]

\[ y_y = \frac{x_D}{R + 1} \]

\[ q \text{ line} \]

\[ \tan \alpha = \frac{q}{q - 1} \]

\[ y_w = x_w \]

\[ y_D = x_D \]

\[ N_{\text{theoretical}} = 7 \]

\[ R, q, x_w, x_D, x_F \]
Simple calculation methods for initial estimations

- Calculation of the minimal number of theoretical plates.
  - gives us information about the difficulty of the desired separation,
  - needed: desired compositions of overhead and bottoms products.
- Minimal reflux ratio: to achieve the desired separation, reflux ratio has a minimal value.
- Number of theoretical plates: with McCabe – Thiele method.
- Calculation of column diameter.
Load factor

- Load factor \((F_{\text{load}})\):
- Depends on: linear velocity of vapour in the empty column \((v)\) density of vapour \((\rho_G)\).
- Density of vapour is influenced by: average molar mass (composition!), temperature \((P, x)\), pressure. Pressure is lowest at top, highest at bottom of column.

\[
F_{\text{load}} = v \sqrt{\rho_G}
\]

\[
\frac{m}{s} \sqrt{\frac{\text{kg}}{\text{m}^3}} = \text{Pa}^{1/2}
\]

\[
\rho_G = \frac{P \cdot \bar{M}}{R \cdot T}
\]

\[
P = P_0 + \Delta P \cdot N_{\text{real}}
\]
Plate efficiency

Operation range: horizontal part
Calculation of column diameter

\[
v = \frac{F_{\text{load}}}{\sqrt{\rho G}}
\]

volumetric flow rate at top and bottom

\[
\dot{V} = V \frac{R_{\text{const}} \cdot T_t}{P_0}
\]

\[
\dot{V} = V' \frac{R_{\text{const}} \cdot T_a}{P}
\]

\[
v = \frac{\dot{V}}{A} = \frac{\dot{V}}{D_o^2 \pi} = \frac{4\dot{V}}{D_o^2 \pi} = \frac{4\dot{V}}{4}
\]

\[
D_o = \sqrt{\frac{4\dot{V}}{v \pi}}
\]

- Selection of load factor value,
- calculate diameter at top and bottom \((D_0)\),
- select a suitable value in between.

\(R_{\text{const}}\) is the ideal gas constant 8.314 J/(mol*K)
Simple calculation methods for initial estimations

• Calculation of the minimal number of theoretical plates.
  – gives us information about the difficulty of the desired separation,
  – needed: desired compositions of overhead and bottoms products.

• Minimal reflux ratio: to achieve the desired separation, reflux ratio has a minimal value.

• Number of theoretical plates: with McCabe – Thiele method.

• Calculation of column diameter.

• Calculation the height of the column.
Height of column

• Determine \( N_{\text{theoretical}} \).

• Read average plate efficiency \( \eta_{\text{plate}} \) and calculate the number of real plate. Round up.

\[
N_{\text{real}} = \frac{N_{\text{theoretical}}}{\eta_{\text{plate}}}
\]

• Multiply with plate height.

\[
H = N_{\text{real}} \cdot \Delta H
\]
Plate columns – topics covered

- Theoretical and real plates
- Operation
- Calculation of $N_{\text{min}}$, $R_{\text{min}}$ McCabe – Thiele method, plate efficiency
- Load factor
- Construction.
Bubble-cap plate
sieve plate

downcomer

weir
Valve plate
Operation of valve trays
Packed columns

- Random or structured packing.
- Random packing is cheaper, but less efficient (same height less separation efficiency).
- Modern structured packing can be applied from laboratory scale to large industrial scales.
Determination of the heights of the column 1.

\[ H = N \cdot \text{HETP} \]

HETP = Height Equivalent to a Theoretical Plate

Sulzer Mellapak packing
Determination of the heights of the column 2.

- Instead of theoretical plates the term transfer units might be also applied.
- NTU (Number of Transfer Units)
- HTU (Height of a Transfer Unit)
- To be calculated separately for the upper and lower sections of the column. Only the active height is calculated.

\[ H = HTU_1 \cdot NTU_1 + HTU_u \cdot NTU_u \]
Theoretical background

\[ V \cdot d y = K_y \cdot a \cdot \Phi \cdot A \cdot (y^* - y) \cdot d H \]

- \( V \) molar flow rate of vapour at top of column (mol/s),
- \( K_y \) mass transfer coefficient (mol/(m\(^2\)\cdot s)),
- \( a \) relative surface area of packing (m\(^2\)/m\(^3\)),
- \( \Phi \) wetting coefficient(-),
- \( A \) cross section of column (m\(^2\)),
- \( y^* = m x \) virtual vapour concentration which would be in equilibrium with the liquid concentration (-).
Theoretical background – the two film theory

\[ y_{Ai} = mx_{Ai} \]

\[ J_A = \beta_x (x_A - x_{Ai}) = \beta_x (x_A - x_{Ai}) \frac{m}{m} = \beta_x (y_A^* - y_{Ai}) \]

\[ J_A = \beta_y (y_{Ai} - y_A) \]

\[ \frac{J_A m}{\beta_x} = y_A^* - y_{Ai} \]

\[ \frac{J_A}{\beta_y} = y_{Ai} - y_A \]

\[ J_A \left( \frac{m}{\beta_x} + \frac{1}{\beta_y} \right) = y_A^* - y_{Ai} + y_{Ai} - y_A \]

\[ J_A = K_y (y_A^* - y_A) \]
Calculation of the heights of the column

\[ V \cdot d\ y = K_y \cdot a \cdot \Phi \cdot A \cdot (y^* - y) \cdot dH \]

\[ dH = \frac{V}{K_y \cdot a \cdot \Phi \cdot A} \cdot \frac{d\ y}{y^* - y} \]

\[ H = \int_0^{H_f} dH = \frac{V}{K_y \cdot a \cdot \Phi \cdot A} \int_{y_F}^{y_D} \frac{d\ y}{y^* - y} \]

\[ HTU_u = \frac{V}{K_y \cdot a \cdot \Phi \cdot A} \quad NTU_u = \int_{y_F}^{y_D} \frac{d\ y}{y^* - y} \]

\[ HTU_l = \frac{V'}{K_y \cdot a \cdot \Phi \cdot A} \quad NTU_l = \int_{y_W}^{y_F} \frac{d\ y}{y^* - y} \]
Calculation of HTU

known: $F, R, q, x_F, x_D, x_W$

$$F = W + D$$

$$F \cdot x_F = W \cdot x_w + D \cdot x_D$$

$$F \cdot x_F = W \cdot x_w + D \cdot x_D = W \cdot x_w + (F - W) \cdot x_D$$

$$W = \frac{F(x_F - x_D)}{x_w - x_D}$$

$$D = F - W$$

$$V = (R + 1) \cdot D$$

$$V' = V + (q - 1) \cdot F$$

$$HTU_u = \frac{V}{K_y \cdot a \cdot \Phi \cdot A}$$

$$HTU_l = \frac{V'}{K_y \cdot a \cdot \Phi \cdot A}$$
Calculation of NTU

\[ \frac{1}{y^* - y} \]

\[ y_D \]

\[ y_F \]

\[ y_W \]

\[ y_D^* - y_D \]

\[ y_F^* - y_F \]

\[ y_W^* - y_W \]

\[ x_W \]

\[ x_F \]

\[ x_D \]

\[ NTU_l \]

\[ NTU_u \]
Random packing
Random packing / rings

- Raschig-ring
- Pall-ring
- Cascade ring
Random packing / saddles

Berl-saddle

Intalox-saddle

Super intalox-saddle
Further random packing elements

- Snowflakes
- Konjugated rings
- Lessing-ring
Further random packing elements

Envipack spheres

Spiral packing
Sulzer packing
in various types and different materials

Support grid
for the packing

Liquid collector

Feed pipe
to distributor

Liquid distributor
mounted on locating grid

Locating grid

Steam inlet pipe

Column sump

Circulation pipe
to reboiler

Skirt

Anchorage

Variations on the above design
Feed:
• vapor
• two phases with flash box
Side stream:
• liquid from collector
• vapor collector

Bottom product
Structured packing
Structured packing types of distillation
Liquid distributors
Grids
Locating grids
The column sleeve is lowered into the column with two cranes. Weight: 100 tons

Installation of the liquid distributor
Economical optimum

(cost [euro/year])

capital cost
operating cost
investment cost

$R_{min}$  $R_{opt}$  $R = \text{reflux ratio} \ [\text{-}]$
Economical optimum

\[ \dot{Q}_{\text{reb}} = V' \lambda_w = \]
\[ = [V + (q - 1) F] \lambda_w = \]
\[ = [(R + 1) D + (q - 1) F] \lambda_w \]

\[ \dot{Q}_{\text{cond}} = V \lambda_D = \]
\[ = (R + 1) D \lambda_D \]
Thank you for your attention!