Hydrodynamic Layout of Columns

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1. Introduction

Columns are used for absorption, distillation and rectification as well as for liquid-liquid extraction. The phase contact for absorption and extraction can be as well co-current flow as counter-current flow. For rectification always counter-current flow is used.

In principle columns can be divided into 4 types:
- without internals
- tray columns
- wetting columns
- columns with rotating internals

In this script tray and wetting columns will be described. Columns without internals are used for absorption and extraction whereas columns with rotating internals are only used for extraction.

Columns with internals are used for absorption and rectification to guarantee an intensive contact of both phases and connected to this a good mass and heat transfer. Depending on the system which has to be separated and on the given flow rates either tray columns or wetting columns are used.

For selecting the type of column different criteria have to be taken into account:
- separation efficiency
- material selection and amount of material
- pressure drop
- loading capacity
- flexibility to changes in loading
- service charge and susceptibility to failure
- costs
- foaming behaviour of the compounds
- contamination tendency

The difference between tray and wetting columns is the kind of mass transfer. For wetting columns the mass transfer takes place at the surface of the liquid film which is present the surface of the internals. The up-flowing gas phase passes this liquid film so that mass and heat transfer takes place. Contrary to this the mass transfer in tray columns takes place in the sparkling layer on each tray. Gas and liquid phase are intensively mixed in the sparkling unit.

Trays are used as column internals if
- large pressure drops are tolerable
- because of large flow rates large column diameters have to be used
- the danger exists that the column will be contaminated or crusted because of media including solid particles
**Wetting internals** have the benefits of

- low pressure drop
- low material costs for usage for non corrosive media
- low sensibility for foaming mixtures

The hydrodynamic design of tray and wetting columns is an essential point of plant design. A column operates only in a defined loading area. In the case of going over the lower or upper boundary of the loading area will result in a drastic decrease of the separation efficiency. For the dimension of a column loading the gas or vapour velocity of the free column cross section is used. The allowable vapour velocity depends on the kind and dimension of the tray or wetting internal, on the loading of liquid phase and on the mixture of substances.

For wetting columns the allowable vapour velocity is chosen in that way that the pressure drop is not too high and the separation efficiency is as large as possible. Further discrimination between the pressure drop of a dry and of a wetted filling is done (the pressure drop of a wetted filling is higher). Increasing vapour velocity results in retaining the down flowing liquid. The free sections for the streams are reduced and the pressure drop increases. In parallel to this effect the mass transfer and the separation efficiency increase because of higher turbulences in both phases (liquid and vapour). Reaching the flooding point the whole column is filled with liquid phase. A further increase of the vapour velocity results in a large increase of the pressure drop and in low separation efficiency. The optimal separation efficiency is reached close below the flooding point.

For the determination of the maximum allowable vapour velocity for tray columns the gas loading factor or F-factor is introduced. This factor depends on the tray distance, the kind of flowing of the phases and especially on the surface tension, which influences the drop sizes. The gas loading factor has to be determined experimentally and can be taken from publications of tray or column producing companies.
2. Tray Columns

2.1. Introduction

A tray is defined as a horizontal tray including openings for passing the vapour and liquid phases. Trays are used in the same way as wetting internals for intensifying the phase contact and for producing a large surface for good mass transfer for thermal separation processes.

A tray column consists of single trays adjusted one over the other. The liquid phase flows from each tray to the next lower tray. The liquid enriches with the high volatile compounds while flowing over each single tray. The height of the liquid level is fixed by the height of weir at the tray outlet. The gaseous phase passes the open areas of the tray, enters the liquid phase at the tray and is dispersed in the liquid. By this a sparkling layer is produced where the mass transfer takes place. The gaseous phase enriches with the light volatile compounds and goes up to the next higher tray.

The mass transfer is characterised by the amount of dispersion of the discontinuous phase in the second continuous phase. Depending where the resistance of mass transfer is situated two different working regimes are possible:

- bubble regime
- droplet regime

Bubble regime

For a lot of trays a closed liquid phase is present during the gas-liquid contact. The surface of the in the liquid phase raising gas flow represents the mass transfer area. The gas phase is dispersed in the continuous flowing liquid phase. The bubble regime is used for these substance mixtures where the mass transfer resistance is on the liquid side.
Droplet regime

The surface of fine dispersed liquid droplets represents the contact area in spraying columns. Because of high gas velocities and of additional introduced mechanical energy the liquid is dispersed. For the droplet regime the gas phase is the continuous phase. The mass transfer resistance is on the gas side.

Film regime

In wetting columns the liquid film flowing down along the surface of the internals is responsible for the mass transfer. The gaseous phase passes over this liquid film without penetrating it. The mass transfer area correlates therefore with the surface of the liquid film.

Tray columns are operated as well in crossflow as in counter-current flow. Based on this counterflow-trays and crossflow-trays are differed.

Crossflow-trays have weirs at the liquid outlet and have the advantage of higher separation efficiency and larger surface areas compared with counterflow-trays. The stability and equal efficiency of the mass transfer is controlled by the adjustment of the down-comers.

The mass transfer area which is present for the dispersion of the gaseous phase is reduced with increasing numbers of down-comers. For an optimal design of these columns a balanced relation between adaptation for liquid flow rate and effective usage of the crossflow-tray for the gaseous phase is necessary.
The efficiency of a tray column is characterised by following parameters:

- dimension of area of operation
- pressure drop of the gaseous phase over the column
- distance between trays
- high efficiency for as well the single tray as for the total column height

The optimal design of tray columns enables the operation at high loadings and low pressure drop by guaranteeing high separation efficiencies.

### 2.2. Working area of tray columns

The maximum possible loading of a tray column is important for the design because by this the minimum possible column diameter is fixed. At constant loading of liquid phase and an increasing gas phase loading the columns starts to flood. At the flooding point no continuous down flowing liquid film is present. New introduced liquid will be entrained by the up flowing gas phase. The liquid content in the column increases as well as the pressure drop over the total height of the column.

The optimal operation area is located close under the flooding point. In this situation a wide surface area of the phases is present for the mass transfer und the best mixing of the phases exists.

The flooding of a tray column can be achieved also at constant gas loading and with increasing liquid loading. The down comers and other opening for the liquid flow are not able to handle the high loadings and therefore the liquid content and the pressure drop of the column increase.

The two different kinds of flooding are treated separately for the design of tray columns. **Entrainment flooding or priming jet flooding** indicates the flooding process because of increasing gas loading, **down flow flooding** the process because of increasing liquid loading.

The minimum possible capacity of a column is limited by the degree of wetting and a sufficient enough phase contact. Different trays vary by the ability of good separation efficiency at low gas and liquid loadings. Valve trays can be used even for very low gas loadings because the valves close at low gas loading. For the same use are bubble cap trays with a safety closing system at low gas loading.

For all kind of trays the loadings are given where a complete phase contact is not possible anymore.
2.2.1. Hydraulic Characteristics

**Dry pressure drop \( \Delta p_t \) [mm WS]**

The dry pressure drop results by the gas flow through the dispersion units without any liquid at the trays.

**Wet pressure drop \( \Delta p_w \) [mm WS]**

The wet pressure drop results if the tray is covered with liquid.

**Height of crest over weir \( h_{0W} \) [mm FS]**

The height of crest over weir defines this height of liquid by flowing over the weir.

**Liquid gradient across tray \( \Delta \) [mm FS]**

The dispersion unit causes a certain flow resistance. Based on this resistance results a tailback of the liquid at higher liquid flow rates. This tailback causes different height of liquid at inlet and outlet weir.

2.2.2. Downflow Flooding [1]

Columns with crossflow trays can flood because of high liquid flow rates. The calculation of the height of liquid level \( h_F \) in the down comer results from following equation:
\[ h_F = h_t + h_W + h_{ow} + h_{da} + \Delta \]  \hspace{1cm} (1)

with

- \( h_t \) .... total pressure drop across tray [mm liquid]
- \( h_W \) .... height of weir at tray outlet [mm liquid]
- \( h_{ow} \) .... height of crest over weir [mm liquid]
- \( h_{da} \) .... head loss due to liquid flow under down comer apron [mm liquid]
- \( \Delta \) .... liquid gradient across tray [mm liquid]

It has to be taken into account that \( h_F \) is calculated for a pure liquid phase. The liquid phase in the down comer is mixed with gas so that the liquid bubbles and foams. Therefore \( h_F \) is corrected

\[ h'_F = \frac{h_F}{\phi_F} \]  \hspace{1cm} (2)

with

- \( \phi_F \) .... relation of the foam density to the liquid density

The value of \( \phi_F \) depends on the separation tendency of the liquid and gas phase.

For systems with low liquid and gas densities, low viscosity of the liquid phase and reduced foaming tendency the gas separates relatively fast from the liquid phase. Typically values of \( \phi_F \) are in this case 0.5. For systems with more stable foams (high gas and liquid densities, high viscosity of the liquid) the values of \( \phi_F \) are 0.2 to 0.3.

Abb.5: Pressure drop for a crossflow tray
2.2.3. Entrainment Flooding [1]

The gas phase flows with a certain velocity through the column. With increasing gas flow rate also the gas velocity increases. At the flooding point the in the column introduced liquid cannot flow down but is withdrawn by the upreaching gas phase. This gas velocity is indicated as gas velocity at flooding point.

This kind of flooding is indicated by Souders and Brown by following equation

\[ c_g = \frac{w_g}{\sqrt{\frac{\rho_g}{\rho_l - \rho_g}}} \]  

(3)

with

- \( c_g \) .....loading factor [m/s]
- \( w_g \) ....gas velocity [m/s]
- \( \rho_g \) .....density of the gas phase [kg/m³]
- \( \rho_l \) ......density of the liquid phase [kg/m³]

\[ w_{g,\text{flood}} = c_{g,\text{flood}} \left( \frac{\sigma}{20} \right)^{0.2} \left( \frac{\rho_l - \rho_g}{\rho_g} \right)^{0.5} \]  

(4)

with

- \( w_{g,\text{flood}} \) .....gas velocity at flooding point [m/s]
- \( \sigma \)...............surface tension [mN/m]

2.2.4. Pressure Drop

The pressure drop of a tray is the difference in pressure between the two vapour phases below and above the tray. The total pressure drop of the column results by the sum of the single pressure drop per tray.

Following parameters of the column are influenced by different pressure:

- temperature profile
- vapour - liquid equilibrium
- vapour loading, because the density of the gas depends on pressure and temperature.

It has to be taken into account that the pressure drop of a tray has to lower than the highest static pressure of the liquid in the downcomer. Otherwise the gas phase would retain the liquid phase in the downcomer and the liquid cannot flow downwards.

The pressure drop has the highest influence for vacuum distillation. For high differences of the pressure between top and bottom of the column a lower vacuum is necessary. Strong fluctuating pressures influence further the temperature profile of the column.
The total pressure drop $\Delta p_{\text{ges}}$ of a tray results in

$$\Delta p_{\text{ges}} = \Delta p_{\text{D}} + \Delta p_{\text{L}}$$

with

$\Delta p_{\text{D}}$ .... pressure drop of the dispersion unit (dry opening for sieve trays, dry valves for valve trays, dry bubble caps and slots for bubble cap trays)

$\Delta p_{\text{L}}$ .... pressure drop of the liquid-gas dispersion on the tray

2.2.4.1. Pressure Drop of the Dispersion Unit [1]

This calculation is used for a rough estimation of the pressure drop by the dispersion unit. The pressure drop of different dispersion units $\Delta p_{\text{D}}$ is calculated by varying following equation:

$$\Delta p_{\text{D}} = K_1 + K_2 \frac{\rho_g}{\rho_l} w_g^2$$

with

$w_g$ .... gas velocity through the opening of the dispersion unit (cap, valve,....) [m/s]

$K_1, K_2$ .... characteristic values

2.2.4.1.1. Determination of $K_1$ and $K_2$ for different kinds of trays

bubble cap tray

$K_1$ represents for bubble cap trays the pressure drop of the gas phase in the slots of the cap.

$$K_1 = 3,73 \left( \frac{\rho_g}{\rho_l - \rho_g} \right)^{1/2} \frac{h_{S,G}^{1/2}}{w_g^{1/2}}$$

with

$h_{S,G}$ .... height of the slots of the cap [mm]

$w_g$ .... gas velocity through the slot [m/s]

For the calculation of $K_2$ following diagram is used.
Sieve trays

For sieve trays always $K_1 = 0$ and $K_2 = 50.8/C_v^2$. $C_v$ is calculated from figure 7. This discharge coefficient for gas flow $C_v$ represents the ration of effective to theoretically possible outlet velocity.

Valve trays

$K_1$ and $K_2$ depend on the opening of the valve. They depend further on the weight and form of the valves and are given by the producers.

2.2.4.2. Pressure Drop of the Gas-Liquid-Dispersion [1]

The pressure drop of the foaming liquid at the tray is calculated by following equation:

$$\Delta p_l = \beta h_{ds}$$

with

$\beta$ ........ aeration factor [no dimension]

$h_{ds}$ ....... calculated height of the clear liquid over the dispersion unit [mm]

The aeration factor $\beta$ represents the amount of gas bubbles in the liquid height. For the calculation only few methods are available. For a rough estimation values from table 1 can be taken.
Table 1: aeration factor $\beta$ depending on comparable air velocity $w_{g,v}$ and gas containing liquid height for bubble cap trays

<table>
<thead>
<tr>
<th>$w_{g,v}$ [m/s]</th>
<th>0.5 $h_S + h_{st} + h_{\bar{u}W}$ [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>0.85 0.80 0.75 0.70 0.65 0.60 0.55</td>
</tr>
<tr>
<td>40</td>
<td>0.80 0.75 0.70 0.65 0.60 0.55 0.50</td>
</tr>
<tr>
<td>50</td>
<td>0.75 0.70 0.65 0.60 0.55 0.50 0.45</td>
</tr>
<tr>
<td>60</td>
<td>0.70 0.65 0.60 0.55 0.50 0.45</td>
</tr>
<tr>
<td>70</td>
<td>0.65 0.60 0.55 0.50</td>
</tr>
<tr>
<td>80</td>
<td>0.60 0.55</td>
</tr>
<tr>
<td>90</td>
<td>0.55</td>
</tr>
</tbody>
</table>

Figure 8 represents the aeration factor and the relative froth density in dependence of the gas loading factor or the $F$-factor.

The relative froth density represents the ratio of the pressure drop over a gas containing liquid [mm] and the actual height of the froth $h_f$ [mm]

$$\phi = \frac{h'_f}{h_f} \tag{9}$$

2.2.4.2.1. Calculation of the height of the clear liquid $h_{DS}$

For sieve and valve trays:

$$h_{ds} = h_W + h_{\bar{u}W} + \frac{\Delta}{2} \tag{10}$$

For bubble cap trays:

$$h_{ds} = h_s + h_{\bar{u}W} + \frac{\Delta}{2} \tag{11}$$

with

- $h_W$ ...... height of the weir
- $h_{\bar{u}W}$ .... height of crest over weir
- $\Delta$ .......... liquid gradient across plate
- $h_S$ ......... static slot seal (height of weir minus height of slot)
The value of $h_S$ is fixed by selection of height of weir and from of the cap.

**Height of weir**

The height of weir is responsible for the pressure drop and the separation efficiency of a tray column. The selection of height of weir depends on the kind of trays.

**Table 2:** Height of weir for different types of trays

<table>
<thead>
<tr>
<th>Height of weir [mm]</th>
<th>Vacuum distillation</th>
<th>Atmospheric distillation</th>
<th>Absorption pressure distillation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Valve trays</td>
<td>20 ÷ 40</td>
<td>30 ÷ 50</td>
<td>40 ÷ 70</td>
</tr>
<tr>
<td>Bubble cap trays</td>
<td>20 ÷ 30</td>
<td>30 ÷ 70</td>
<td>40 ÷ 100</td>
</tr>
<tr>
<td>Sieve trays</td>
<td>10 ÷ 20</td>
<td>20 ÷ 50</td>
<td>40 ÷ 80</td>
</tr>
<tr>
<td>S-trays</td>
<td>40 ÷ 50</td>
<td>50 ÷ 80</td>
<td>60 ÷ 100</td>
</tr>
</tbody>
</table>

For bubble cap trays the height of weir should not be much higher than the height of the chimney. If the chimneys are higher than the liquid layer on the tray this has a positive effect for the stability.

**Liquid gradient across plate**

The liquid gradient across the plate is an essential parameter characterising the operation of different tray types. The across the tray flowing liquid has a gradient, which is especially of importance at high liquid loadings and large column diameters.

For the calculation different methods are available depending on the kind of tray.

**Calculation of height of crest over weir** $h_{uw}$

**for plane weirs**

$$h_{uw} = 664 \left( \frac{\dot{L}}{l_W} \right)^{2/3}$$  \hspace{1cm} (12)

with

- $\dot{L}$ ......liquid flow rate [m$^3$/s]
- $l_W$ ......length of weir [m]
for jagged weirs

\[ h_{\text{W}} = 851 \left( \frac{L}{\tan \frac{\theta}{2}} \right)^{0.4} \]  
(13)

with

\( \theta \) angle of the jag
\( L \) ......liquid flow rate [m³/s]

for round weirs

\[ h_{\text{W}} = 44.300 \left( \frac{L}{d_{\text{W}}} \right)^{0.704} \]
(14)

with

\( d_{\text{W}} \) .....diameter of the weir [mm]
\( L \) ......liquid flow rate [m³/s]

The calculations are based on clear liquid.

2.2.5. Entrainment flooding [1]

Entrainment flooding represents the process if liquid drops are withdrawn at high gas velocities. By this effect lower volatile liquid is withdrawn to the tray above where liquid with higher volatility is present. This effect reduces the efficiency of the tray.

2.2.6. Tray efficiency

The efficiency of a tray depends on

- composition of the system, physical and chemical parameters
- flow rates of gas and liquid phase
- type and dimension of the tray
2.3. Design of tray columns by Stichlmair

Calculation of the maximum F-factor $F_m$

$$F_m = 2.5 \left[ \phi^3 \sigma_l \left( \rho_l - \rho_g \right) g \right]^{1/4}$$  \hspace{1cm} (15)

with:
- $\sigma$ .... surface tension [N/m]
- $g$ .... gravity force [m/s$^2$]
- $\rho_l$ .... density of the liquid phase [kg/m$^3$]
- $\rho_g$ .... density of the gas phase [kg/m$^3$]
- $\phi$ .... relative free cross section
Following equation is used for determination of the relative free cross section $\phi$

$$\phi = \frac{A_H}{A_{AK}}$$

(16)

with

$A_H$......Area of holes, slots [m$^2$]

$A_{AK}$....active area [m$^2$]

$$A_{AK} = \frac{\dot{V}_g}{w_g}$$

(17)

with

$\dot{V}_g$ ....volumetric gas flow rate [m$^3$/s]

$w_g$ ....allowable gas velocity [m/s]

The maximum gas loading $F_m$ is present if the height of the gas-liquid dispersion is equal to the distance between two trays. By increasing the distance of the trays also higher gas loadings are possible.

Calculation of the allowable $F$-factor

$$F \approx 0.7 F_m$$

(18)

Calculation of the active tray area related to the gas velocity $w_g$

$$F = w_g \sqrt{\rho_g}$$

$$w_g = \frac{F}{\sqrt{\rho_g}}$$

(19)

Calculation of the column area $A$ and the column diameter $d_K$

$$A = A_{AK} - 2A_D$$

(20)

with

$A$ ......total area of the tray [m$^2$]

$A_D$......area of the downcomer [m$^2$]

$$d_K = \sqrt{\frac{4A}{\pi}}$$

(21)

$d_K$......diameter of the column [m]
2.4. Systematic of column trays

Column trays can be divided by following criteria depending on:

- kind of liquid direction (with and without enforcement direction)
- kind of two phase flow (countercurrent flow or cross flow)
- kind of flow direction (rotation flow, cross flow, turn round flow)
- kind of try type and operation regime

Cocurrent liquid flow

A cocurrent liquid flow is present if the liquid phase flow on each tray in the same direction. This kind of liquid flow is relatively seldom used.

Countercurrent liquid flow

The direction of the liquid flow is different from one tray to the next.

The efficiency of a tray is characterised by

- loading
- pressure drop
- separation efficiency

The separation efficiency is influenced by following constructive details:

- The fragmentation of the tray area fixes the maximum loading of gas and liquid phase.
- The maximum gas capacity is fixed by the distance between the trays.
- The height, where the gas phase has to pass the liquid, is fixed by the height of weir and the design of the dispersion units.
- An enlargement of the downcomers increases the liquid loading of the column.
- The kind of liquid flow results by the adjustment of the downcomers.

To guarantee the operation conditions of trays following points have to be taken into account:

- insensitive against operation changes like chancing gas and liquid loadings
- large enough distance from one try to the next to prevent entrainment of drops to next following tray
good separation efficiency by enough height for passing the gas through the liquid

high active mass transfer area

2.4.1. Trays without enforced liquid direction

For this kind of trays no downcomers for the liquid phase are installed. By this the liquid and the gas phase have to pass through the same passage units.

To prevent a raining through of the liquid a certain height of liquid at the tray has to be produced. The height of the liquid on the trays is increasing if the gas velocity is increase, because higher gas loading holds more liquid on the trays. The operation method is called "pulsating" because gas and liquid phase have to pass alternative through the opening.

By special construction it can be achieved that the liquid is flowing down at certain areas of the tray. (Kittel tray).

2.4.1.1. Turbogrid tray

The gas and the liquid phase flow alternative through the slots and the liquid is dispersed by this into small droplets. This kind of tray is used for large liquid flow rates or at high constant gas loadings.

2.4.1.2. Sieve tray without enforced liquid direction

This kind of tray is operated as countercurrent tray. Gas and liquid phase pass alternative through the holes in the tray. A minimum gas flow rate is necessary to guarantee mass transfer at the tray. The upper loading limit is reached if the gas flow retains all the liquid on the tray and the liquid cannot flow down anymore.

This kind of tray cannot be used for systems with changes in the loading and for systems including solids, because the solid particles will block the holes.

As geometric specific value the hole area relation (= area of holes of the tray / area of the tray) is used. An optimal hole area relation is the basic for separation efficiency and should reach values of 0,10 to 0,30, depending on the kind of separation process.
<table>
<thead>
<tr>
<th>Specific value</th>
<th>Vacuum distillation</th>
<th>Atmospheric distillation</th>
<th>Absorption pressure distillation</th>
</tr>
</thead>
<tbody>
<tr>
<td>hole area relation</td>
<td>0.25 ÷ 0.30</td>
<td>0.15 ÷ 0.22</td>
<td>0.10 ÷ 0.18</td>
</tr>
</tbody>
</table>

2.4.1.3. Kittel tray without downcomer

For Kittel trays (Fig. 11) gas and liquid phases pass through the same passage openings. By adjustment of the slots the liquid is forced in a certain direction on the tray. This kind of tray can be designed as radial flow tray, which means the liquid flows down once in the centre and the next time at the column wall.

2.4.1.4. Ripple-tray

Ripple trays (Fig. 12) have the same mode of operation as turbogrid trays. The area of the ripple tray is nearly sinusoidal and to guarantee an equal distribution of the liquid the ripple of one tray to next is changed by 90°.

The gas phase passes through the top of the ripple while the liquid flows down at the bottom of the ripple.
2.4.2. Trays with enforced liquid direction

The enforced liquid direction is achieved by using downcomers. In the downcomer the liquid enters the next tray independent from the way of the vapour. The horizontal liquid flow is chosen depending on the problem. The construction is designed that way, that neither the liquid can pass through the openings of the vapour nor the vapour can pass through the downcomers of the liquid.

Possible liquid directions on the tray are:

- Reverse flow
- Radial flow
- Cross flow

**Reverse Flow Tray**

In the middle of the tray a separation weir is installed. Around this weir flows the liquid, so that inlet and outlet are at the same side of the tray. These trays are used for low liquid loadings and a low liquid gradient across the tray. The separation weir has to be higher than the downcomer weir. By the separation weir dead zones on the tray may occur.

**Radial Flow Tray**

At the radial flow trays the liquid enters in the middle of the tray, flows radial over the tray and at the outside over the weir. Circular downcomer weirs are used, guaranteeing a constant height of liquid on the tray.

The direction of the liquid can be either in the same or in the opposite direction. For the cocurrent liquid direction special trays with a slope towards the middle are used. Because of the length of the downcomer weir this kind of tray is used for high liquid loadings and the risk of liquid tailback is minimised by this kind of weir. The cocurrent liquid direction enables higher separation efficiency, but parallel the constructive expense is higher.
Cross-Flow-Tray

Cross flow trays are often used, because they are universal trays. They are divided into single and multi pass cross flow trays.

Single-Pass Cross Flow Tray

For the single pass tray the liquid flows across the tray from the inlet to the outlet. The direction of the liquid on trays one on the top of the other is countercurrent.

Multi-Pass Cross Flow Tray

For high liquid loadings multi pass trays are used to prevent a liquid tailback on the tray and to minimise the liquid gradient across the tray. This liquid tailback causes a raining through of the liquid through the opening of the vapour phase. Multi pass cross flow trays give shorter ways of the liquid on the weir and because of separation the liquid amount the liquid gradient is lower. The effective usable area of the tray is reduced because of higher area of downcomers.
Stepped Tray

Stepped trays are used for high liquid flow rates and for large column diameters. They are used for equalising different liquid heights, which arise especially at high liquid flow rates.

2.4.2.1. Classical Trays with Enforced Liquid Direction

Further trays with enforced liquid direction are:

- Bubble Cap Tray
- Tunnel Tray
- Valve Tray
- Sieve Tray with downcomer
- S-Tray

2.4.2.1.1. Bubble-cap tray

The bubble cap tray is a cross flow tray because the liquid flows across the tray from the inlet to the outlet. The caps are mounted in regular distances across the tray, where the edge points of equilateral triangles are chosen.

In the tray holes or chimneys for passing of the vapour are installed. The chimneys are covered by the cap, which forces the vapour to leave the cap in a parallel flow to the tray and passes through the liquid. By this the sparkling layer is produced, where the mass transfer takes place.

The chimneys prevent a raining through of the liquid to the tray below. By the help of the downcomer weir a constant level of the liquid on the tray is produced, so that the bubble cap tray is very useful for variable operation conditions. This ability of constant mass transfer over a wide filed of liquid and vapour loadings is called flexibility. The bubble cap tray operates in a wide field of loadings with good separation efficiency. With modern flat caps also the pressure drop could be reduced.
Different kinds of bubble caps are used for different loadings and a selection of cap forms is shown in the figure:

- conventional bubble cap (1)
- flat cap (2)
- Sigwart cap (3)
- Umbrella cap (4)
- Varioflex-cap (5)
- Varioflex-cap with valve flap (6)

**Hydraulic Characteristics**

By the hydraulic characteristics the operation area of the bubble cap is fixed. Within the operation area optimal flow conditions are present at the tray so that the tray operates with high efficiency and balances variations of the loadings very well.

At low gas and liquid loadings both phases pass alternately through the slits. The tray is in **pulsating operation**. To prevent this effect a minimum gas loading is necessary.
Increasing the liquid loading at constant low gas loading result in the effect of raining through. Because of too low kinetic energy of the gas the liquid can pass through the holes of the vapour. This effect takes place especially for large trays and for high liquid loadings.

To prevent high liquid levels on the tray the height of the weir should not be much higher than the height of the chimney. This guarantees a better stability of the tray. Also negative is a too low liquid loading because a sufficient flow of the liquid over the weir is not present which leads to irregular flowing down from the tray and dead zones arise on the tray.

At low liquid loading, increasing gas loading and by this reduced dynamic dipping into the liquid channels can be blown free. The free blowing of slits results in a reduced mass transfer, because the gas phase has no contact with the liquid phase. This effect occurs if the slits are completely open and the vapour loading is further increased.

At high gas and high liquid loadings liquid droplets can be withdrawn to the upper tray. The separation efficiency is reduced and at the upper tray flooding can begin.

The advantages of the bubble cap tray are the large operation area and the good separation efficiency. The disadvantage is the relatively high pressure drop (special cap trays achieve pressure drops of 2 mbar per tray) and also the problems for systems with solid particles, because cleaning is difficult to handle.

2.4.2.1.2. Tunnel Trays

The principal of tunnel trays is the same as for bubble cap trays, so that this kind is used also for large diameters.

The tunnels can be parallel or crosswise to the liquid flow, also circular tunnels are available.

The chimneys are of rectangular form and covered by the cover. Dimensions of the channel and of chimney, height of chimney and height of dipping into liquid are designed for different operations.

Tunnel tray with tunnels parallel to flow direction

This kind is used in most cases as cross flow tray. The liquid flows through the parallel to the flow direction installed tunnels and the gas phase passes the chimneys and through the liquid. A constant liquid height is guaranteed by the downstream weir.
Hydrodynamic Layout of Columns

Tunnel trays with tunnels crosswise to the flow direction or Thormann-tray

The vapour chimneys are covered by hoods and through the slits in the hoods the vapour is directed in a given direction into the liquid. This forced flow pushes the liquid over the tray and so the ways of the liquid and the residence times are longer.

The Thormann-tray is used for high gas loadings and middle to low liquid loadings. Because of the longer residence time and the forced vapour direction the separation efficiency is better than of bubble cap trays. Because of the low pressure drop this tray is also for used for operation under vacuum.

Tunnel tray with ring tunnels

This tray is constructed as radial tray. The inlet of the liquid is central and flows to the edge of the tray and over the weir to the tray below. The vapour enters over the chimneys and the ring tunnel into the liquid.

The working area is a little bit lower than of bubble cap trays but especially for low loadings the ring tunnel tray works better.

2.4.2.1.3. S-Tray (Uniflux tray)

This kind of tray exists of S-forms with in most cases trapezium slits. The vapour phase passes through the slits of the S-element and forces the liquid into the direction of the downcomer weir.

This kind of tray is suitable for high vapour and high liquid loadings and is comparable with a bubble cap tray. The maximum vapour loading is a little bit higher than of bubble cap trays.
2.4.2.1.4. Valve Trays

The group of valve trays is characterised by very good flexibility. The dynamic operation, which means that the height of the valve and with this the open area for the vapour adjusts to the vapour loading, guarantees for this trays a large operation area with high separation efficiency and large flexibility.

General demands for the separation elements are:

- high velocity of the gas phase at the contact area with the liquid
- possible lower pressure drop
- variability of the outlet opening area for different vapour loadings

The number of valves is calculated by the maximum vapour loading. A further increase of the separation units is not allowed, because reaching the lower loading limit results in raining through of the liquid and reduces therefore the separation efficiency dramatically.

Valve trays are suitable also for systems with solid particles, because the opening and closing of the valve acts as a self cleaning effect. In contrary the bubble cap trays are very sensible to solid particles, which might block the separation unit.

Valve trays are the most used kind of trays and took over the leadership from the bubble cap trays.

The dry pressure drop of valve trays is lower than this of bubble cap trays, because the valve trays do not need a chimney for the vapour. The most important influence factor for the dry pressure drop is the weight of the valve.
The operation characteristic of a valve tray can be separated into three areas according the pressure drop.

In area 1 the valve is closed. The starting opening distance guarantees that the valve is not fixed to the tray. The vapour phase can pass through the opening.

Increasing the gas velocity results in opening the valve. Area II characterises the field between closed and maximum opened valve. The maximum is fixed by the maximum opening distance. In this area the pressure drop is nearly constant.

Area III is characterised if at maximum opening the vapour velocity is further increased. Here the outlet velocity of the vapour increases and with this also the pressure drop increases. For practical use is area II and III.
Different design forms are used:

- Ballast-Valve
- Float-Valve
- Flexitray

**Ballast Valve Tray**

The in figure 13 shown ballast valve is a standard valve with three feet. This valve moves vertically in a cycle opening in the tray and the opening depends on the gas velocity. By a groove in the tray this valve is fixed against rotation.
Float Valve Tray

A float valve is shown in figure 16. The vapour phase flows through the slits into the liquid phase. The openings are closed at low extremely low gas loading and at low loadings the lighter part of the cap opens. Increasing the vapour loading results in total opening of the cap. The vapour entrance into the liquid is horizontal and reduces the free blowing. The liquid flows as cross flow over the tray. Depending on the diameter and on the liquid loading of the tray the float valve tray can be constructed as 2 or more passing trays.

The float valve tray can be used for high liquid and vapour loadings.

Flexitray

This kind of valve consists of a cycle sheet, which is situated over a hole in the tray. The maximum opening is fixed by a crossing with 4 feet. Depending on the vapour loading the cycle sheet is lifted and by decreasing gas velocity the valve closes, so that a raining through of the liquid is prevented.

A further possibility is to use valves of different weight, where valves with the same weight are mounted parallel to the downcomer weir. With this a good distribution at different vapour loading can be achieved, because at low gas loading first the valves with low weight open and afterwards also these with higher weight.

Cocurrent Valve Trays

For this kind of valves one foot of the valve is designed shorter resulting in an unequal opening of the valve. The valve opens therefore in one favourite direction and the vapour enters the liquid in one direction, which can force a positive or negative transport of the liquid.
2.4.2.1.5. Sieve Trays

Sieve trays can be constructed with and without downcomer, so with and without forced liquid flow direction.

**Sieve Tray with forced liquid direction**

This kind of tray operates as crossflow tray. The openings for the gas phase are holes in the tray and the direction of the vapour is not changed by caps or valves. No chimneys or cover of the holes are available, so that a minimum gas loading must be present to prevent a raining through of the liquid. At high vapour loadings the risk of entrainment of fine liquid droplets increases.

A special form of the sieve tray is the sieve slit tray. For this from the tray slits under a certain angle are produced. Depending on the construction a positive or negative transport effect can be achieved. The direction of the gas phase is horizontal and the mass transfer is more intensive at negative transport effect because of longer residence time. The risk of liquid entrainment is reduced.
2.4.2.1.6 Jet-Tray

From the tray straps are stamped out and liftet. These straps are for the vapour stream, which enters the liquid parallel to the tray. A minimum gas velocity is necessary equal to the sieve tray to prevent raining through of the liquid. Because of the easy construction the production costs are low.

2.4.2.1.7 Kittel Tray with Downcomer

The Kittel-tray forces the liquid in one direction because of the design of the slits. The inlet and outlet at the tray is alternative from the middle and from the edge of the tray (countercurrent liquid flow). The Kittel tray works in a wide operation field. Of disadvantage might be the fine distribution of the gas phase which is a problem especially with systems that have the tendency of foaming. By this the tray efficiency and the capacity are reduced.

2.4.2.1.8 Perform-Contact-Tray

Perform-Contact-Trays are designed as coss flow trays. On the active area stretched metal segements are mounted and the slits are in a sharp angle to the liquid flow direction. The vapour phase passes these slits and has a positive transport effect on the liquid. The entrance weir has only a distribution effect and guarantees a good liquid distribution on the tray. A downcomer weir is not necessary, because an element for holding back the liquid is not necessary based on the design of the Perform-Contact Tray.

Further installations are flow breakers, which are in a sharp angle to the gas flow, acting as separator and represent an increase of the active tray area.

Perform-Contact-Trays have a high operation area and a low pressure drop. Especially for systems including solids this tray is used. Because of the positive liquid transport effect this tray can be constructed even for high liquid loadings in single pass form.
2.4.2.2. Operation Areas of Different Tray Types

An optimal tray construction should represent at high loadings a low pressure drop and a high separation efficiency at low costs. A value for the loading of the tray are the liquid and vapour loadings, where always the minimum and maximum values are given.

An optimal mass transfer of a tray is achieved by:

♦ a long contact time between dispersed and continuous phase achieved by increase of liquid height on the tray
♦ a good dispersion to increase the mass transfer area

Higher turbulences are achieved by higher vapour velocities. It has to taken into account that the risk of entrainment (fine liquid droplets flow with the vapour stream to the tray above) increases with high gas velocities. This results in lower separation efficiencies of the tray and the pressure drop increases because of higher liquid height on the tray.

The efficiency of a tray is determined by

➢ Operation area
➢ Pressure drop
➢ Separation efficiency

For estimating the operation area of a tray the relationship of minimum to maximum vapour velocity is used. For bubble cap trays, tunnel trays and Thormann trays the maximum gas velocity of the free column area, this is the column cylinder without any trays, is calculated. For sieve trays, valve trays and high efficiency trays the minimum gas velocity is determined, where the vapour is able to hold back the liquid on the tray.

To compare the working area of different tray types following trays were tested in a 2 m column:

− bubble cap tray
− valve tray
− Perform-Contact-Tray (PCT)
Figure 22 shows the working areas of different standard trays. Perform-Contact-Trays are preferable for high liquid loadings. Comparing the working area of bubble cap tray and valve tray shows that valve trays are designed for higher liquid flow rates. Further it is clear that bubble cap trays and valve trays with light valves work best at high vapour loadings.

For Perform-Contact-trays the operation area is shifted to higher vapour loadings with larger slit wideness, but the relationship of maximum to minimum vapour loading is dramatically reduced at larger slit wideness.

For the same tray types pressure drop curves were determined (see figure 23). The higher and lower value of the pressure drop result for different liquid loading of the tray. The minimum and maximum vapour loading are represented by the side lines as comparable air velocities.

The experiments are determined in most cases with air-water mixtures instead of vapour-liquid-mixtures. For comparison a "comparable air velocity" is defined:

$$w_{g,v} = 28,9 w_g \left( \frac{\rho_g}{\rho_l} \right)^{0.5}$$  \hspace{1cm} (22)

The values determined with air-water-mixture can be directly calculated for the real vapour velocities with equation 22.
From figure 23 it is visible that the pressure drop of Perform-Contact-Trays, especially with slit widthness over 3 mm, is much lower than of other comparable trays at the same vapour loading. This low pressure drop results from the missing of a downcomer weir and no liquid gradient across the tray. Because of this high operation area of the Perform-Contact-Tray it is called also high efficiency tray.

An exception is the 2 mm Perform-Contact-Tray, which represents very high pressure drops. The use of this tray is limited for separation problems with high vapour loadings where the pressure drop is not significant.

For comparison of the separation efficiency of different trays, the different efficiencies are compared with the maximum value of the bubble cap tray. It is obvious that the valve trays achieve the best separation efficiencies.
Abb. 24: Comparison of different separation efficiencies with the maximum separation efficiency of the bubble cap tray.

Comparing stretched metal trays with bubble cap trays show that the separation efficiency of a bubble cap tray is reached only at comparable air velocities over 2.1 m/s. The efficiency of bubble cap trays cannot be reached.

For Kittel-Centrifugal-trays with downcomer higher separation efficiencies can be reached which are even higher than that of bubble cap trays at high loadings.

From the comparison of the different tray constructions (sees table 4) it is obvious that at 85% of the maximum loading nearly all trays reach the same separation efficiency. Comparing the total pressure drop and the flexibility shows that these tray types with low pressure drop are on the other side less flexible.
Table 4: Comparison of different tray designs

<table>
<thead>
<tr>
<th>Tray type</th>
<th>Working area $V_{\text{max}}/V_{\text{min}}$</th>
<th>Enhancement relation</th>
<th>Flexibility</th>
<th>Total pressure drop at 85% maximum loading [mm WS]</th>
<th>Costs related to bubble cap tray [N/m$^2$]</th>
<th>weight [N/m$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bubble cap</td>
<td>4 - 5</td>
<td>0,8</td>
<td>0,6 - 0,8</td>
<td>80</td>
<td>45 - 80</td>
<td>1</td>
</tr>
<tr>
<td>Tunnel</td>
<td>3 - 4</td>
<td>0,6 - 0,7</td>
<td>0,55 - 0,65</td>
<td>50</td>
<td>50 - 85</td>
<td>0,8</td>
</tr>
<tr>
<td>Thormann</td>
<td>4 - 6</td>
<td>0,85</td>
<td>0,7 - 0,9</td>
<td>80</td>
<td>45 - 60</td>
<td>0,8</td>
</tr>
<tr>
<td>Valve (Koch)</td>
<td>5 - 8</td>
<td>0,8</td>
<td>0,7 - 0,9</td>
<td>80</td>
<td>45 - 60</td>
<td>0,7</td>
</tr>
<tr>
<td>Valve (Glitsch)</td>
<td>5 - 8</td>
<td>0,8</td>
<td>0,7 - 0,9</td>
<td>80</td>
<td>40 - 60</td>
<td>0,7</td>
</tr>
<tr>
<td>Sieve</td>
<td>2 - 3</td>
<td>0,8</td>
<td>0,7 - 0,8</td>
<td>55</td>
<td>30 - 50</td>
<td>0,7</td>
</tr>
<tr>
<td>Kittel</td>
<td>2 - 3</td>
<td>0,8</td>
<td>0,7 - 0,8</td>
<td>40</td>
<td>20 - 50</td>
<td>0,6</td>
</tr>
<tr>
<td>Turbogrid</td>
<td>1,5 - 2,5</td>
<td>0,7</td>
<td>0,6 - 0,8</td>
<td>10</td>
<td>25 - 40</td>
<td>0,5</td>
</tr>
</tbody>
</table>

For comparison of different column trays also the costs have to be taken into account. A direct comparison is given in figure 25, where it is obvious that valve trays and stretches metal trays are essentially cheaper than bubble cap trays. Basic for this comparison are trays made from carbon steel.
3. Packed Columns

3.1. Introduction

Internals are different formed bodies, which fill the column either as random bulk or as arranged packings. Internals are used for thermal separation processes like absorption, distillation and extraction. They have the great advantage of offering a large phase boundary for these separation processes at good economy.

In this chapter only the usage for gas-liquid systems is described. The liquid entrance is at the top of the column and because of gravity force flows over the internals. The gas entrance is below the bulk good and the upflowing gas passes over the fine liquid film. The surface area of the liquid film is essentially for the heat and mass transfer.

For successfully operation of packed columns further internals are necessary, which have to be adjusted to the separation problem so that the efficiency and the working area of the column is not limited. The efficiency can be reduced by

- bad liquid distribution
- entrainment of liquid droplets
- irregular gas distribution
- additional pressure drop
- incomplete wetting of the internals

The materials of the available internals are very different and for the selection the resistance and price is essential. The selected internals should have high separation efficiency at lowest possible pressure drop. Separation efficiency and pressure drop increase with decreasing diameter of the internals and as consequence the operation area is reduced.

The selection criteria for internals are:

- chemical, thermal and mechanical resistance
- long term behaviour
- hydraulic capacity
- pressure drop
- wettability
- operation at partial loading
- pollution tendency
- weight
- ability for balancing of irregular phase distribution
- mass transfer behaviour
- costs
Chemical, mechanical and thermal resistance have to be calculated always together with long term behaviour. The hydraulic characteristic is influenced by the maximum gas- and liquid loading. For the hydraulic calculation the flooding point is determined, which is the theoretical maximum hydraulic loading. The wettability is of importance for low liquid loadings. The wetting characteristic responds to this part of the internal surface, which is active for the mass transfer. The mass transfer behaviour is calculated by the height of a transfer unit (HTU).

For the selection of the suitable material the relationship of stability to the costs have to be calculated more carefully. Internals abrade because of chemical and thermal treatment. Special long term stable materials have a much longer life time, but the costs are much higher. Further influence for the life time of the internals are temperature, chemical composition of the mixture, contact time and further stress factors to the material.

**Metallic Internals** represent high values for the mechanical strength and coefficient of elasticity, so that these internal can be produced with low wall thickness. This is positive for the voids fraction ($\varepsilon$) and for the specific surface (a). Also the risk of breaking is reduced in comparison with ceramic internals. Possible corrosion effects have to be taken into account.

**Ceramic Internals** represent good chemical resistance against inorganic and organic acids (exception HF). Further the thermal resistance is present for temperatures up to 1.800 °C. Of disadvantage is the brittleness and the ability of breaking, further the restriction of temperature changes and higher loss because of mechanical abrasion.

Ceramic materials are a mixture of clay (kaolin), flux material (feldspar) and quartz. Each of these materials has different influence on the chemical and thermal behaviour of ceramic. Flux material act as solidifying material during burning process and influence the sinter and melting temperature. Quartz increases the voids fraction ($\varepsilon$) and the stability for temperature changes. Kaolin influences the formability and the thermal stability.

**Stoneware** is the most often used material, which is resistance against most acids and hot alkaline materials. For **Porcelain** chemical-technical porcelain is used, which has a higher mass than stoneware and a better resistance against alkali materials.

**Plastic Internals** have the properties of lower density, high viscosity and low coefficient of elasticity. Based on the lower weight the filling of the columns can be performed easily. The resistance can be increased by adding of stabiliser and fillers. Of disadvantage are low thermal stability and aging, which results in embrittlement of the plastic and consequently mechanical forces result in cracking.

The most used plastic material is **polypropylene (PP)**, which is suitable for working temperatures up to 120°C and has a good resistance against acids, bases and a lot of organic solvents. **Polyethylene (PE)** is comparable to PP, but suitable only for temperatures up to 80°C. **Polyvinylchloride (PVC)** is resistant against alkali and chlorine and can be used up to 60°C. With polyvinylidenefluoride (PVDF) temperatures up to 140°C can be handled.
In table 5 the resistance of ceramic, metal and plastic materials against different media is compared. These values are an overview for the possible use of the different materials.

Table 5: Comparison of material stability

<table>
<thead>
<tr>
<th>Medium</th>
<th>Stoneware</th>
<th>Porcelain</th>
<th>Steal</th>
<th>Stainless steal</th>
<th>PP</th>
<th>PVC</th>
<th>PVDF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acetone</td>
<td>A 200</td>
<td>A 200</td>
<td>A 200</td>
<td>A 60</td>
<td>D 20</td>
<td>C 25</td>
<td></td>
</tr>
<tr>
<td>Benzene</td>
<td>A 200</td>
<td>A 200</td>
<td>A 200</td>
<td>B 20</td>
<td>D 20</td>
<td>A 80</td>
<td></td>
</tr>
<tr>
<td>Butanol</td>
<td>A 200</td>
<td>A 200</td>
<td>A 200</td>
<td>A 40</td>
<td>B 60</td>
<td>A 80</td>
<td></td>
</tr>
<tr>
<td>Butanone</td>
<td>A 200</td>
<td>A 200</td>
<td>A 200</td>
<td>C 60</td>
<td>D 20</td>
<td>D 40</td>
<td></td>
</tr>
<tr>
<td>CCl₄</td>
<td>A 200</td>
<td>C 40</td>
<td>C 40</td>
<td>C 20</td>
<td>D 20</td>
<td>B 60</td>
<td></td>
</tr>
<tr>
<td>CHCl₃</td>
<td>A 200</td>
<td>A 200</td>
<td>A 200</td>
<td>D 20</td>
<td>D 20</td>
<td>A 100</td>
<td></td>
</tr>
<tr>
<td>Chlorine (wet)</td>
<td>A 200</td>
<td>D</td>
<td>D</td>
<td>D 20</td>
<td>B 20</td>
<td>A 100</td>
<td></td>
</tr>
<tr>
<td>Acetic acid 5 %</td>
<td>A 120</td>
<td>D</td>
<td>B 120</td>
<td>A 100</td>
<td>A 60</td>
<td>A 125</td>
<td></td>
</tr>
<tr>
<td>Ethanol</td>
<td>A 150</td>
<td>B 150</td>
<td>C 150</td>
<td>A 80</td>
<td>A 40</td>
<td>A 100</td>
<td></td>
</tr>
<tr>
<td>H₃PO₄ 10 %</td>
<td>C 120</td>
<td>C 65</td>
<td>A 95</td>
<td>A 100</td>
<td>A 60</td>
<td>A 150</td>
<td></td>
</tr>
<tr>
<td>HCl 10 %</td>
<td>A 120</td>
<td>D</td>
<td>D</td>
<td>A 100</td>
<td>A 60</td>
<td>A 150</td>
<td></td>
</tr>
<tr>
<td>HF</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>A 60</td>
<td>A 20</td>
<td>A 100</td>
<td></td>
</tr>
<tr>
<td>HNO₃ 10 %</td>
<td>A 120</td>
<td>D</td>
<td>A 120</td>
<td>A 20</td>
<td>A 60</td>
<td>A 100</td>
<td></td>
</tr>
<tr>
<td>K₂Cr₂O₇</td>
<td>A 200</td>
<td>A 200</td>
<td>A 200</td>
<td>–</td>
<td>A 60</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>KOH 30 %</td>
<td>C 40</td>
<td>B 95</td>
<td>B 95</td>
<td>–</td>
<td>A 60</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>Methanol</td>
<td>A 150</td>
<td>B 150</td>
<td>C 150</td>
<td>A 60</td>
<td>A 40</td>
<td>A 100</td>
<td></td>
</tr>
<tr>
<td>NaOH 30 %</td>
<td>C 40</td>
<td>B 80</td>
<td>B 95</td>
<td>A 100</td>
<td>A 60</td>
<td>A 50</td>
<td></td>
</tr>
<tr>
<td>Phenol</td>
<td>A 95</td>
<td>B 180</td>
<td>B 150</td>
<td>A 40</td>
<td>A 60</td>
<td>A 120</td>
<td></td>
</tr>
<tr>
<td>Toluene</td>
<td>A 200</td>
<td>A 200</td>
<td>A 200</td>
<td>B 20</td>
<td>D 20</td>
<td>A 75</td>
<td></td>
</tr>
<tr>
<td>Trichloroethylene</td>
<td>A 200</td>
<td>D</td>
<td>C 95</td>
<td>B 60</td>
<td>D 20</td>
<td>A 80</td>
<td></td>
</tr>
</tbody>
</table>

A no influence of the medium  
B normally good stability  
C reduced operating time  
D Usage not recommended / no data

The numbers are the highest operation temperature in °C for continuous operation.
3.2. Design of Internals

Internals can be divided into standard and high performance internals.

3.2.1. Standard Internals

**Spherical Internals** represent the simplest regular form of internals. Bulks with spherical internals have a relatively low surface per bulk volume and because of the low void fraction the pressure drop is relatively high. Materials are porcelain and stoneware.

**Cylindrical Internals** represent the simplest form of standard internals. They have 30% higher surface than spherical internals and have high mechanical stabilities. The materials are ceramic, metal, plastic or even glass.

For the saddle internals the smooth surface equalises the vapour and liquid flows and a good chemical stability is achieved. Standard materials are plastics and ceramic.

**Raflex-Rings® (Rauschert) / Pall-Rings® (VFF)** are comparable internals. These standard internals are usable for nearly all separation problems. The open structure gives an equal sprinkling and reduces the pressure drop. The materials are metal, plastic or ceramic. Design in plastic and metal allow high vapour velocities and good mass transfer.

3.2.2. High Performance Internals

**Hiflow-Rings® (Rauschert)**. The catwalk construction gives high mechanical stability and high void fractions. The low weight allows large bulk volumina and guarantees high gas and liquid loadings. The sensibility against pollution is very low. The large number of edges and corners present many points for droplets.

Special formed internals made in plastic are collected under the name **grid internals**. The surface is structured with many catwalks. The surface area for the mass transfer is much higher than the simple geometric surface. Larger open sectors in the cylindrical area reduce the flow resistance and higher gas and liquid flow rates are possible.
Hacketten® (VFF) und Hedgehog -Internals® (VFF) have a spherical form with many grids. This gives the possibility of constant liquid distribution.

3.3. Fluid Dynamics In Packed Columns

3.3.1. Geometrical Marking

Random bulk internals and structured packings are characterised by the nominal diameter $d_a$, the bulk volume related to the geometric surface $a$ and the voids fraction $\varepsilon$.

The nominal diameter $d_a$ represents the outer main dimension of a single internal. For spherical and cylindrical internals it is equal to the edge length of the surrounding cube. For saddle internals no specific diameter is available. The voids fraction increases with larger nominal diameter. Metal internals have larger voids fractions than plastic internals because of lower wall thickness.

$$a = \frac{A_P}{V_K}$$

(23)

$$\varepsilon = \frac{V_K - V_P}{V_K}$$

(24)

with

$\varepsilon$ ........voids fraction [m$^3$/m$^3$]

$a$ ........specific surface, is equal to the relation of geometric surface to the bulk volume [m$^2$/m$^3$]

$V_K$......volume of the column [m$^3$]

$V_P$......solid volume of the internals inside the column [m$^3$]

$A_P$......total surface of the internal bulk [m$^2$]

From the geometrical surface and the voids fraction the calculative particle diameter $d_p$ (for spherical internals equal to the diameter of the sphere), and the hydraulically diameter of the bulk $d_h$ can be calculated. Based on the model that internal bulks include parallel channels void of the bulk can be calculated by the voids fraction $\varepsilon$ and the medium flow velocity in the bulk can be calculated with $w_s = w/\varepsilon$.

Abb. 31: Hedgehog Internal®.
\[ d_p = 6 \cdot \frac{V_p}{A_p} = 6 \cdot \frac{1 - \varepsilon}{a} \]  
\[ d_h = 4 \cdot \frac{f}{u} \]  

with

\[ f \ldots \text{free flow cross section [m}^2\text{]} \]

\[ u \ldots \text{wetted circumference of the bulk [m]} \]

From this following equation results:

\[ d_h = 4 \cdot \frac{V_p}{O} \]  

with

\[ V_P \ldots \text{volume of the bulk [m}^3\text{]} \]

\[ O \ldots \text{wetted surface of the internals [m}^2\text{]} \]

For taking the wetted surface \( O \), under negotiation of flow dead zones, equal the surface of the internals, the hydraulic diameter \( d_h \) can be calculated by following equation:

\[ d_h = 4 \cdot \frac{\varepsilon}{a} = \frac{2}{3} \cdot \frac{\varepsilon}{1 - \varepsilon} \cdot d_p \]  

With increasing wall thickness the voids fraction \( \varepsilon \) is reduced and with this the hydraulic diameter as well as the specific surface. The wall thickness depends on the material of the internal. The maximum allowable pressure drop and the risk of pollution limit the hydraulic diameter.

Taking the wall thickness \( s \) into account gives for \( a \) and \( \varepsilon \):

\[ \varepsilon = \left( \frac{d_h}{d_h + s} \right)^2 \]  
\[ a = \frac{4 \cdot d_h}{(d_h - s)^2} \]  

To achieve a high equal distribution of gas and liquid phase over the cross section area the dimension of the internals should not be too large. A recommended value is:

\[ \frac{d_k}{d_p} \geq 10 \]
with

\[ d_K \ldots \text{diameter of the column} \]
\[ d_P \ldots \text{diameter of the internal} \]

This recommended value can be increased at high liquid loadings and for good wettability of the internal bulk.

### 3.3.2. Operation Area

The knowledge of the hydraulic characteristics in the whole operation area and especially for the flooding limits, combined with the maximum loading, are essential for the design of packed columns.

The operation area of a packed column is limited by the maximum loadings, which depend on the characteristic of the phases, the type and geometry of the internals. The upper limit is called **flooding point** and the lower limit **dewetting point**.

Reaching the *loading point* the down flowing liquid phase is hold back by the up flowing gas phase. This results in higher liquid content in the bulk and so an increase in the gas pressure drop. Further increase of the loading gives the flooding point. The liquid cannot flow downwards, single flows combine to larger ones, which flow downwards as single phase on certain points of the column. On the other side the vapour phase passes as single phase without contact to the liquid the column. A strong segregation of the phases and a rapid increase of the pressure drop results. A further increase of the loading results in a rapid decrease of the separation efficiency.

![Operation area of packed columns](image)

**Abb. 32:** Operation area of packed columns.

The area between loading point and flooding point represents the optimum operation area of the column. The gas phase cannot pass the column without contact of the liquid. Some liquid is hold back, where the gas is dispersed. Because of high turbulences of both phases the result is a good mass transfer and so high separation efficiency.
The lower limit is fixed by the minimum liquid flow, which guarantees an equal wetting of the internals. With decreasing wetting of the internals the mass transfer area is reduced and the separation efficiency of the column decreases. The lower limit is influenced by physical properties of the mixture to be separated as well as from material and geometry of the internals.

3.3.2.1. Calculation of the Flooding loading

Depending on the internals and the liquid loadings two kinds of flooding can occur:
- Flooding for large internals with phase inversion at high phase loadings \((\dot{L}/\dot{G}\) high)
- Flooding based on entrainment of liquid droplets by the gas phase at low phase ratios \((\dot{L}/\dot{G}\) low)

For small internals with low voids fraction \((\varepsilon = 0.4 – 0.75 \text{ m}^3/\text{m}^3)\) many voids are present acting as dead zones, which will be filled with liquid when increasing the liquid loading. If the total column is filled with a continuous liquid phase the gas phase passes in from of bubbles through the column. This condition is called phase inversion, because the originally continuous gas phase becomes the dispersed phase.

Bulks with high performance internals contain large voids fractions \((\varepsilon = 0.92 – 0.98 \text{ m}^3/\text{m}^3)\) with a low amount of dead zones. Because of this open structure from the liquid film droplets are withdrawn by the gas phase. with increasing liquid loading the amount of liquid droplet entrainment increases. The operation area of such bulks is much higher than of standard internals.

3.3.2.1.1. Droplet Forming in Packed columns

Droplets are formed at
- the edges of the internals
- higher gas velocities by transforming the kinetic energy of the gas phase to the liquid phase

Droplets are withdrawn by the gas phase from the liquid film (pull-off force \(F_R\)). The separated droplet has to overcome in the balance situation further the gravity force reduced by the lifting force \((F_G – F_A)\).

\[
F_R = F_O + (F_G – F_A)
\]

gravity force \(F_G\):
\[
F_G = \frac{\pi}{6} d_t^3 \rho_l g
\]

lifting force \(F_A\):
\[
F_A = \frac{\pi}{6} d_t^3 \rho_g g
\]
By a balance of forces the minimum effective gas velocity for pull-off of a droplet from the liquid film can be calculated.

The drop formation is described by the dimensionless Weber number $\text{We}_l$, which is the relation of the pull-off force $F_R$ to the surface force $F_O$. For low viscous systems ($1 \text{ mPa} \cdot \text{s}$) the value is $12 \cdot 2 \varepsilon^2 / C_R$. Below this value no droplets can be formed and the column is filled with a continuous liquid phase. This effect arises for high liquid loadings, for systems with low surface tension and for bulks with low voids fraction.

$$
C_R \rho g d_T w_g^2 \frac{\sigma_i}{\varepsilon} = \frac{\text{We} \cdot C_R}{\varepsilon^2}
$$

(33)

with

- $d_T$ ....... droplet diameter [m]
- $\rho_l$ ....... liquid phase density [kg/m$^3$]
- $\rho_g$ ....... vapour phase density [kg/m$^3$]
- $g$ ....... Earth's acceleration [9.81 m/s$^2$]
- $\sigma_i$ ....... surface tension [N/m]
- $w_g$ ....... gas velocity [m/s]

### 3.3.2.1.2. Droplet Discharging

For discharging the formed droplets in the bulk a high enough gas velocity is necessary. In figure 33 $F_G$ represents the gravity force, $F_A$ the lifting force and $F_S$ the propulsive force of the gas, which is necessary for building a droplet.

$$
F_S = F_G - F_A
$$

(34)
The propulsive force $F_S$ is

$$F_S = \frac{\zeta \pi}{4} d_T^2 \rho_l \frac{w_g^2}{2}$$

with

- $d_T$ ....... droplet diameter [m]
- $\rho_l$ ......... liquid density [kg/m$^3$]
- $\rho_g$ ......... gas density [kg/m$^3$]
- $g$ ........ Earths acceleration [9,81 m/s$^2$]
- $\zeta$ ........... resistance coefficient
- $w_g$ ...... gas velocity [m/s]

For the force balance for droplet discharging following equation follows:

$$\zeta \frac{\pi}{4} d_T^2 \rho_l \frac{w_g^2}{2} = \frac{\pi}{6} d_T^3 (\rho_l - \rho_g) g$$

(35)

The theories for determination of the flooding point velocity are divided into two groups:

- For this kind of calculation it is suggested that at the flooding point droplets are formed in the voids of the bulk which are discharged by the gas phase (Sherwood, Shipley, Hollaway, Eckert, Leva)
- The second theory suggests that the downflowing liquid file is hold back in the voids at a certain gas velocity, so that the column is filled with liquid ($\dot{L}/\dot{G}$ high). From a certain continuous liquid height the column starts flooding (Mersmann)

### 3.3.2.1.3. Calculation of Flooding Loading By Sherwood, Shipley und Hollaway

In 1938 Sherwood et al. gave the first correlation for determining the upper loading limit, which is given in equation (36):

$$\left( \frac{w_g^2 a_P \rho_g}{g e^3 \rho_l} \right)^{0.2} = f \left( \frac{\dot{L}}{\dot{G}} \sqrt{\frac{\rho_g}{\rho_l}} \right)$$

(36)

with

- $w_g$ ............... velocity in the empty column [m/s]
- $a_P$ ............... total surface of the internals [m$^2$/(m$^3$ bulk)]
- $e$ ............... voids fraction
- $g$ ............... Earths acceleration [9,8067 m/s$^2$]
- $\dot{L}$ ............... mass flow liquid [kg/(s$\cdot$m$^2$)]
- $\dot{G}$ ............... mass flow gas [kg/(s$\cdot$m$^2$)]
- $\rho_l$ and $\rho_g$ ... density of liquid and gas phase [kg/m$^3$]
The measurements for following diagram for determination of the flooding point by Sherwood et al. were performed with the system air-water.

\[ \eta \quad \ldots \ldots \quad \text{dynamic viscosity [mPa\cdot s oder cP]} \]

Abb. 34: Model for flooding point velocity by Sherwood et al., \( U_f^2 \) is \( w_g^2 \) and \( \mu^{0.2} \) is \( \nu^{0.2} \)

### 3.3.2.1.4. Flooding Loading by Billet [7]

Billet controlled the Sherwood equation with experiments with thin wall metal internals and recognised that the kind of filling the column has a significant influence on the separation efficiency, the pressure drop and the maximum loading capacity. By different methods of filling the internals into the column the bulk density changes and with this the voids fraction. the higher the bulk density the better is the separation efficiency and the loading, but the pressure drop increases too.

Billet found only small correlation for the experimental data and the by the Sherwood equation calculated values. He saw the reason in deviation of the packing and a too
large factor for potentialisation of the liquid viscosity. He took the packing factor from Eckert $F_P = aP/\varepsilon^3$ and the density relation of water to the liquid phase $\psi$.

The packing factor includes the different influenced of internal sizes and forms and of the internal material.

Billet determined following equation for the upper loading limit:

$$w_g = CO_D \left( \frac{aP_g}{\varepsilon^3 \rho_l} \eta^{0.12} \psi \right)^{-0.5}$$

with

$$C = 3.14$$

$O_D$ ....responds to the for a certain value $\frac{L}{G} \left( \frac{\rho_g}{\rho_l} \right)^{0.5}$ direct reading ordinate value.

### 3.3.2.1.5. Calculation of Flooding Loading By Mersmann [8]

The bulk is suggested to be a system of channels and through all channels flow both phases. The downflowing liquid film influences the shearing stress of the vapour phase. The maximum loading of the column depends on the thickness of the liquid film, which increases with higher liquid loadings and thus reduces the free area for the upflowing gas phase. Passing a certain gas velocity for a given liquid loading results in holding back the liquid film in the voids of the bulk. The liquid does not flow down anymore and the bulk is filled step by step with liquid. If the column is completely full with liquid the liquid phase is the continuous phase and the gas the dispersed phase (phase inversion).

The thickness of the film $\delta$ in the bulk cannot be measured or calculated, so the wetness density is used.

Ordinate value:

$$\Delta \rho \frac{H}{\gamma'} = \zeta \left( 1 - \varepsilon \right) \eta g \gamma_g \left( \frac{\rho_g}{\rho_l} \right)^{0.5}$$

with

$$C\gamma \gamma$$

$\gamma$
$\Delta p_t$...... dry pressure drop  
$H$...... bulk height of the internals [m]  
$\gamma_l$...... specific weight of the liquid [kg/m$^3$]  
$\gamma_g$...... specific weight of the gas [kg/m$^3$]  
$w_g$...... gas velocity [m/s]  
$\zeta$...... resistance factor

The resistance factor $\zeta$ includes the kind of flow of the gas. For laminar flow it is proportional to the kinematical viscosity and for turbulent flow it is calculated by the equation of ERGUN:

$$\zeta = \frac{150}{Re_g} + 1.75 \quad \text{mit} \quad Re_g = \frac{w_g d_g}{v_g (1 - \varepsilon)}$$

(39)

The equation of Mersmann (38) represents the relation of the propulsive force of the gas in the empty column to the gravity force of the liquid depending on the relation of the film thickness to the hydraulic diameter.

**Abb.36:** Dimensionless illustration of the flooding point by Mersmann with experimental values of different authors.
Table 1: Explanation of symbols in figure 36

<table>
<thead>
<tr>
<th>Symbol</th>
<th>author</th>
<th>remarks</th>
<th>Symbol</th>
<th>author</th>
<th>remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>16</td>
<td>16 mm Raschig-Rings</td>
<td>s</td>
<td>4</td>
<td>12,6 mm Raschig-Rings mixture water / air</td>
</tr>
<tr>
<td>b</td>
<td>21</td>
<td>25 mm Raschig-Rings</td>
<td>t</td>
<td>4</td>
<td>Air / CCl4</td>
</tr>
<tr>
<td>c</td>
<td>20</td>
<td>25 mm Raschig-Rings</td>
<td>u</td>
<td>4</td>
<td>Air / CCl4 / C2H5OH-mixture</td>
</tr>
<tr>
<td>d</td>
<td>20</td>
<td>12.4 mm spheres</td>
<td>v</td>
<td>4</td>
<td>Air / CCl4 / C2H5OH-mixture</td>
</tr>
<tr>
<td>e</td>
<td>20</td>
<td>25 mm Berl-Saddles</td>
<td>w</td>
<td>4</td>
<td>Air / CCl4 / C2H5OH-mixture</td>
</tr>
<tr>
<td>f</td>
<td>18</td>
<td>12.4 mm spheres</td>
<td>α</td>
<td>1</td>
<td>Air / Water</td>
</tr>
<tr>
<td>g</td>
<td>19</td>
<td>15 mm Raschig-Rings</td>
<td>β</td>
<td>1</td>
<td>H2 / Water</td>
</tr>
<tr>
<td>h</td>
<td>19</td>
<td>15 mm Berl-Saddles</td>
<td>γ</td>
<td>1</td>
<td>CO2 / Water</td>
</tr>
<tr>
<td>i</td>
<td>19</td>
<td>20 mm Intalox-Saddles</td>
<td>δ</td>
<td>1</td>
<td>Air / aqu. glycerine</td>
</tr>
<tr>
<td>j</td>
<td>17</td>
<td>30 mm Raschig-Rings</td>
<td>ε</td>
<td>1</td>
<td>Air / aqu. glycerine</td>
</tr>
<tr>
<td>k</td>
<td>17</td>
<td>35 mm Berl-saddles</td>
<td>φ</td>
<td>1</td>
<td>Air / aqu. glycerine</td>
</tr>
<tr>
<td>l</td>
<td>17</td>
<td>35 mm Pall-Rings</td>
<td>ρ</td>
<td>1</td>
<td>Air / aqu. glycerine</td>
</tr>
<tr>
<td>m</td>
<td>17</td>
<td>25 mm Pall-Rings</td>
<td>ψ</td>
<td>1</td>
<td>Air / aqu. butyric acid</td>
</tr>
<tr>
<td>n</td>
<td>17</td>
<td>25 mm Intalox-Saddles</td>
<td>χ</td>
<td>1</td>
<td>Air / aqu. butyric acid</td>
</tr>
<tr>
<td>o</td>
<td>17</td>
<td>35 mm Raschig-Rings</td>
<td>χ</td>
<td>1</td>
<td>Air / CH3OH</td>
</tr>
<tr>
<td>p</td>
<td>17</td>
<td>35 mm Pall-Rings</td>
<td>ζ</td>
<td>1</td>
<td>Air / aqu. CH3OH</td>
</tr>
<tr>
<td>q</td>
<td>17</td>
<td>35 mm Intalox-Saddles</td>
<td>ζ</td>
<td>1</td>
<td>Air / aqu. CH3OH</td>
</tr>
<tr>
<td>r</td>
<td>17</td>
<td>35 mm Supersaddles(Steal)</td>
<td>ζ</td>
<td>1</td>
<td>Air / aqu. CH3OH</td>
</tr>
</tbody>
</table>

1       T. K. Sherwood, G. H. Shipley u. F. A. L. Hollaway
4       G. W. Minard u. M. D. Winning
16      H. Schrader
17      T. Teutsch
18      G. Schrewe
19      K. Wiggert
20      B. Deiters
21      A. Mersmann
3.3.2.2. Calculation of the Lower Loading Limit [9]

For the lower loading limit the physical properties of the mixture, the geometric dimensions and the material of the internals are significant. With decreasing wetting the separation efficiency of the column decreases.

For calculation of the lower loading limit $\dot{v}_{l,u}$ Schmidt gives following equation:

$$\dot{v}_{l,u} = 7.710^{-6} \frac{C_{l}^{2.9}}{(1-T_{l})^{0.2}} \left( \frac{g}{a} \right)^{0.5}$$

(40)

with the dimensionless liquid factor $C_{l}$:

$$C_{l} = \frac{\rho_{l} \sigma_{l,g}}{\eta_{l} g}$$

(41)

and the dimensionless shearing stress factor $T_{l}$:

$$T_{l} \cong 0.9 \left( \frac{w_{g}}{w_{g,flood}} \right)^{2.8} = 0.9 \left( \frac{F}{F_{flood}} \right)^{2.8}$$

(42)

$\dot{v}_{l,u}$ ...... specific liquid loading at lower loading limit [m$^3$/m$^2$s]

$\sigma$ ...... surface tension of the gas-liquid system [mN/m]

$\eta$ ...... dynamic viscosity of the liquid [mPa s]

$g$ ...... Earth acceleration [9.81 m/s$^2$]

$\rho_{l}$ ...... liquid density [kg/m$^3$]

$F$ ...... gas loading factor $F = w_{g} \cdot \rho_{g}^{0.5}$

$F_{flood}$ ...... gas loading factor at flooding point
3.3.3. Pressure Drop of Packing Columns

Below the boundary curve $AA$ the pressure drop of the dry and of the wetted bulk are parallel, because the effective free area for the gas phase is nearly similar. This is only the case if the liquid loading is not too high.

Between the curves $AA$ and $BB$ the pressure drop curve of the wetted bulk has a higher slope than the dry bulk. The reason is the reduction of the free area where the gas phase has to pass. The liquid content of the column is until the curve $BB$ independent from the gas velocity.

Above the curve $BB$ both phases start to influence each other. The situation at the curve $BB$ is called loading zone.

For a further increase of the gas loading curve $CC$, the flooding point, is reached. The liquid phase is hold back in the bulk by the gas phase. The gas bubbles through the liquid and the liquid flows downwards in large flows. At further increase of the gas phase the liquid is blown out from the bulk.

At same gas loading the loading zone is reached earlier at higher liquid loadings. The liquid decreases the free area for the upward flowing gas phase. Parallel the vapour pressure increases.

![Diagram](attachment:image.png)

**Abb. 37:** Dependence of the pressure drop (a) and liquid content (b) in a internal bulk from gas velocity and wetting density; $\Delta \rho_s =$ pressure drop; $y$-value in figure b) = related liquid content

3.3.3.1. Calculation Models for Dry Pressure Drop in Packed Columns

The total pressure drop of a packed column is normally divided into the dry pressure drop of the bulk and in the pressure drop of the wetted bulk depending on the wetting density. To produce and keep constant a flow of the liquid phase through the bulk a certain pressure drop is necessary. The flow system can be described by different models:
• Channel model
• Particle model
• Two-Phase model

3.3.3.1.1. Channel Model [10]

For the channel model the internal packing with the height $H$ is replaced by a system of parallel channels with the length $H$, which has the same voids fraction and the same surface as the packing.

For the ideal case laminar flow in the packing is suggested. From this ideal flow always deviations are present and the suggestion of laminar flow is only present at low liquid loadings.

For the pressure drop of the gas it has to be divided into dry and wetted packing. The equation of dry pressure drop is based on the law of Hagen-Poiseuille for smooth pipes:

$$\Delta p_i = \zeta \frac{l \rho_g w_g^2}{\frac{H}{2}}$$  \hspace{1cm} (43)

Introducing the effective gas velocity $w = w_g / \varepsilon$ and the hydraulic diameter $d_h$ gives following equation:

$$\Delta p_i = \zeta \frac{3 \rho_g w_g^2}{4} \frac{1 - \varepsilon}{\varepsilon^3} \frac{H}{d_p}$$  \hspace{1cm} (44)

with

$\zeta$ .......... resistance factor of the packing
$\varepsilon$ .......... voids fraction of the packing [$m^3/m^3$]
$w_g$ ...... velocity of the empty pipe [m/s]
$d_p$ ...... particle diameter of one internal [m]

$$d_h = \frac{2 \varepsilon}{3 (1 - \varepsilon)} d_p$$  \hspace{1cm} (45)

The resistance factor $\zeta$ is a function of the Reynolds number:

$$Re = \frac{w_g d_p}{\nu_g}$$  \hspace{1cm} (46)

with $\nu_g$ ...... kinematical viscosity of the gas [$m^2/s$]
In the literature the dry pressure drop is given without the physically not important factor 2/3 in (45) and without the factor ½ in (43):

\[
\Delta p_t = \zeta \frac{1 - \varepsilon}{\varepsilon^3} \frac{\rho_s w^2 H}{d_p}
\]

Therefore the dry pressure drop depends on the surface of the internal, the form of the edges and the voids fraction, which is influenced depending on the filling in of the internal into the column. The insurance for the exact value of \(\varepsilon\) shows that for the same internals different results for the dry pressure drop can be achieved.

### 3.3.3.1.2. Particle Model

Starting point for this model are the flow resistances at single internals and further the influence of neighbour internals is taken into account. **Stichlmair** describes the voids fraction independent from the Reynolds number:

\[
\frac{\zeta^*}{\zeta_0} = \varepsilon^{-4.65}
\]

with

\(\zeta^*\) .......resistance factor of one internal in a swarm
\(\zeta_0\) .......resistance factor of a single internal
For the pressure drop $\Delta p$ following equation is available:

$$
\Delta p = \frac{3}{2} \zeta_0 \left(1 - \varepsilon\right) H \rho_p \frac{d_p}{2} \frac{W_s^2}{g} 
$$

(49)

The resistance factor $\zeta_0$ of the single internal depends on the type of internal and on the Reynolds number. The Reynolds number is defined as (different from the channel model):

$$
Re = \frac{W_s d_p}{v_g} 
$$

(50)

### 3.3.3.1.3. Two-Phase Flow

A two phase flow includes the influence of the upflowing gas phase and the downflowing liquid phase. If the flows pass the bulk with low velocity, they move through the voids without change of the packing. At higher gas velocities some particles are moved in the boundary area, the rest of the particles keeps without movement. A further increase of the gas loading results in loss of contact of the solid particles. In this condition the packing has the highest voids fraction and an equilibrium between following forces is achieved:

- on one side the measured pressure drop $\Delta p$ between two horizontal layers
- on the other side the weight of the solid and the liquid minus the lifting force and the resistance force produced by the gas:

$$
\Delta p = H \left(1 - \varepsilon\right) \left(\rho_p - \rho_g\right) g 
$$

(51)

To prevent the arising of whirl phase in columns back holding plates are used.

### 3.3.3.2. Pressure Drop of Wetted Packings

If a packed column with gas flow is wetted on the surface of the internals liquid films are produced. The downflowing liquid reduced the relative voids volume, the free area for passing of the gas is reduced and the pressure drop of the gas phase increases. At constant gas velocity for the empty tube the wet pressure drop increases with increasing wetting density.

The liquid content below the loading zone is independent from the gas velocity in the empty tube and increases with increasing wetting density. Above the loading zone the liquid content increases with increasing gas velocity. At the flooding point a continuous liquid phase is produced represented by a dramatically increase of the liquid content in the column.
3.3.3.2.1. Determination of the Flooding Point [10]

The gas velocity at the flooding point is a function of the wetting density. With increasing liquid loading the gas velocity at the flooding point decreases. The dimensionless wetting density is a relationship of the middle thickness of the film related to the hydraulic diameter of the packing:

\[
B^* = \left(\frac{\nu_i}{g^2}\right)^{\frac{1}{3}} \frac{1 - \varepsilon}{\varepsilon d_p} \cdot \frac{\dot{V}_i}{d_h}
\]

with

\[
\dot{V}_i \ldots \text{wetting density} \, [\text{m}^3/\text{m}^2 \text{ s}]
\]

\[
d_h \ldots \text{hydraulic diameter} \, [\text{m}]
\]

(52)

For determining the influence of higher kinematical viscosities of the liquid the dimensionless wetting density \(B^*\) is multiplied with the factor \(\left(\frac{\nu_g}{\nu_i}\right)^{0.3}\).

3.3.3.2.2. Calculation of the Wet Pressure Drop by Teutsch [11]

Based on detailed measurements with the system air-water Teutsch gave following equation for the pressure drop of wetted packings \(\Delta p\):

\[
\Delta p = \Delta p_t a w^{(1+c w_g)}
\]

(53)

with

\[
\Delta p_t \ldots \text{pressure drop of the dry packing}
\]

\[
\nu_i \ldots \text{wetting density} \, [\text{m}^3/\text{m}^2 \text{ s}]
\]

\[
w_g \ldots \text{gas velocity} \, [\text{m/s}]
\]

\[
c \ldots 0,12
\]
Further Teutsch gave following equation including the influence of the flow behaviour and of friction forces:

\[
\frac{\Delta p}{\Delta p_i} = f\left(Fr \cdot Re_i^{-0.8} \left[1 + 5 \cdot 10^{-5} Re_g \right]\right)
\]

with

\[
Re_g = \frac{w_g d_p}{v_g (1 - \varepsilon)} \quad Re_i = \frac{w_i d_p}{v_i (1 - \varepsilon)} \quad Fr = \frac{w_i^2 (1 - \varepsilon)}{g d_p}
\]

Fr \cdot Re_i^{-0.8} represents the reduction of the voids fraction \(\varepsilon\) by the liquid phase. 
\(1 + 5 \cdot 10^{-5} Re_g\) represents a turbulence factor, which can be neglected for \(Re_g < 1500\).

### 3.3.3.2.3. Pressure Drop based on Column Internals

The pressure drop of the gas phase is produced mainly by the bulk of internals. A small amount is produced also by further column internals.

**Support Plates**

These plates carry the weight of the internals, the liquid content and eventually arising pollution. Parts of the free areas are covered by the above laying internals and a reduction of the effective free area is not only produced by the support plates but also by the bulk of internals.

**Redistributors**

Redistributors are used for bringing the liquid from the wall back into the packing. They reduce the free column area so that in this region the hydraulic loading of the column and the pressure drops increases. At high loaded packing columns in this area the flooding point might be reached.

**Back holding plates**

The problems are similar to the support plates, but they do not have to withstand such high forces so that the construction is not so heavy and the problems are lower because of a higher amount of free areas.

**Collector plates**

The upflowing gas phase passes chimneys where the velocity is increased and consequently at the outlet reduced to the velocity of the empty tube. The necessary pressure drop for increasing the velocity cannot be recovered and gives in addition the total pressure drop of the collector plates.
Liquid distributors

Also in the liquid distributors the gas velocity is increased in certain areas, which results in a pressure drop.

Nozzles

Nozzles need for a good distribution of the liquid high liquid pressures. The relative high initial velocity of the liquid is reduced by the upflowing phase, which results in a pressure drop of the gas phase $\Delta p_{DS}$:

$$\Delta p_{DS} = \rho_l \dot{V}_l \Delta w_g$$  \hfill (55)

Demister

In packed columns demisters are used to separate blowing put liquid droplets from the gas phase.
3.4. Layout of Packing Columns

For calculation of the column diameter for a chosen type of internal a hydraulic calculation is performed, determining the flooding point which represents the theoretical maximum loading of the column. For technical realisation this operation area will not be used, because small changes in the gas velocity result in entrainment of the liquid and the column starts flooding. For the praxis columns operate at 80% of the flooding loading, because at these conditions a good mass transfer and a good separation efficiency is present and there are enough safety reserves against flooding of the column.

3.4.1. Design of a Distillation Column by Beck [13]

Following data of the internal are necessary for the layout:

- specific surface \( a \)
- voids fraction \( \varepsilon \)
- calculation diameter \( d_p \)

For the calculation of the diameter of the column further data are necessary:

- Flows together with composition
- density, surface tension, viscosities
- temperature of the flows

The liquid loading of the column has an important influence on the gas velocity. The determination of the gas velocity and further dimension of the column diameter has to be done separately for stripping and enriching part of the column, because the liquid content change dramatically at the point of the feed.

A rough estimation of the column diameter can be done by the loading diagram.

The value \( X \) is calculated by following equation:

\[
X = \frac{L}{V} \sqrt{\frac{\rho_g}{\rho_l}} 
\]

(56)

with

- \( L \) ........ mass flow of the liquid [kmol/h]
- \( V \) ........ mass flow of the vapour [kmol/h]
- \( \rho_l \) ........ liquid density [kg/m\(^3\)]
- \( \rho_g \) ........ vapour density [kg/m\(^3\)]
For determination of value $Y$ first a pressure drop is suggested. The packing factor $F$ can be taken from literature of companies.

$$Y = \frac{10,764Fv^{0.1}}{\rho_v(\rho_i - \rho_g)} v_g^2 \tag{57}$$

With the loading diagram the $Y$ value is determined and in a further step the gas velocity $v_g$ calculated.

With the specific gas velocity the diameter of the column $d_K$ is calculated by following equation:

$$d_K = \sqrt[4]{\frac{4V}{\pi v_g}}$$
with

\( \dot{V} \) ..........mass flow of the gas phase [kg/s]

\( v_g \) ..........specific gas velocity [kg/m\(^2\)/s]

\( \nu_l \) ..........viscosity of the liquid phase [cSt]

To reduce the male distribution of the liquid in the column the relation \( \frac{dK}{dP} \) must be higher than 10. The calculated column diameter is compared with this relation and if necessary it has to be corrected.

If the suggested relation is undergone, smaller internals have to be chosen and the calculation has to be done again.

**Calculation of the Column Height**

\[
H_K = HETP \cdot N_{th}
\]

For the calculation of the column height \( H_K \) the determination of the gas velocity \( w_g \) is necessary. The calculation is done with equation (58).

\[
w_g = \frac{\dot{V}}{\rho_g \frac{d_K}{4}}
\]  

(58)

with

\( \dot{V} \) ..........mass flow of the gas phase [kg/s]

\( \rho_g \) ..........density of the gas phase [kg/m\(^3\)]

\( d_K \) ..........diameter of the column [m]

Beck suggests a dependency of the gas velocity from the liquid loading and so a different calculation of the gas velocity \( w_g \) [m/s] has to be done.

\[
w_{eff} = K_1 \left[ \frac{\rho_l}{\rho_g} \left( 1 - K_2 f(\eta_l) \right) \sqrt{\nu_l} \right]
\]  

(59)

\[
f(\eta_l) = 0,80 + 0,225\sqrt[\nu_l]{\eta_l}
\]

with

\( \eta_l \) ..........dynamic viscosity of the liquid phase [cP], only if \( \eta_l > 1,0 \text{cP} \)

\( K_1, K_2 \ldots \) from company data

\( \nu_l \) ..........liquid loading [m\(^3\)/m\(^2\) h]
\[ w_g = w_{eff} \left[ 1 + 7.5 \left( \frac{d_p}{d_k} \right)^2 \right] \] (60)

with

\[ d_p \ldots \ldots \text{diameter of the internal [m]} \]
\[ d_k \ldots \ldots \text{diameter of the column [m]} \]

Table 2: Diverse constants of internals for maximum liquid loading \( \dot{v}_l \) at \( w_{\text{Air}} = 0.10 \text{ m/s} \).

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<tr>
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<td>125</td>
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<td>0.072</td>
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<tr>
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<td>150</td>
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<td>0.100</td>
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<td>145</td>
<td>185</td>
<td>220</td>
<td>280</td>
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</tr>
</tbody>
</table>

Calculation of the liquid loading \( \dot{v}_l \) [m\(^3\)/m\(^2\)h]

\[ \dot{v}_l = \frac{\dot{L}}{d_k^2 \pi} \] (61)
Calculation of the value $n_{th}$ per m bulk in the packed column

$$n_{th} = \frac{1}{HETP} = \frac{K_1}{w_g} \sqrt{\frac{\rho_l}{\rho_g} \frac{1}{1 + d_K}} \left(1 - K_2 \sqrt{\nu_l}\right) f\left(\frac{d_p}{d_K}\right)$$

(62)

with

$$f\left(\frac{d_p}{d_K}\right) = \frac{1,72}{\left(1 + 7,5 \left(\frac{d_p}{d_K}\right)^2\right)} - 0,72$$

(63)

$Z_K$.....height of the internal bulk [m]

Table 3: Diverse internal constants for minimum liquid loading $\nu_l$.

<table>
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<tr>
<th>Internal [mm]</th>
<th>8</th>
<th>15</th>
<th>25</th>
<th>35</th>
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<td>10,50</td>
<td>12,00</td>
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</tr>
</tbody>
</table>
⇒ Tips for the praxis

To minimize the problems that the liquid enters the column wall, the height of the bulk has to be divided into packings with the height $H_x$ with separate support and back holding plates and liquid distributors.

The height of the packing $H_x$ is calculated by *Eckert*

$$\frac{H_x}{D} \approx 2,5 \div 3,0 \quad \text{Raschig-Rings}$$

$$\frac{H_x}{D} \approx 5,0 \div 8,0 \quad \text{Saddles}$$

$$\frac{H_x}{D} \approx 5,0 \div 10,0 \quad \text{Pall rings}$$

The limitation of $H_x \leq 6,0 \text{ m}$ is guilty for all internals.

3.4.2. Calculation of Distillation and Absorption Columns by Billet [14]

Calculation of resistance value

$$\xi_{\text{flood}} = \frac{g}{C^2_{\text{flood}} \left[ \frac{L}{V} \sqrt{\frac{\rho_g}{\rho_l} \left( \frac{\eta_l}{\eta_g} \right)} \right]^{0.4}}$$

(eq. 64)
Hydrodynamic Layout of Columns

\[ \dot{L} \] mass flow liquid phase [kg/h]
\[ \dot{V} \] mass flow vapour phase [kg/h]
\[ \rho_l \] density liquid phase [kg/m³]
\[ \rho_g \] density vapour phase [kg/m³]
\[ \eta_l \] viscosity liquid phase [kg/ms]
\[ \eta_g \] viscosity vapour phase [kg/ms]
\[ C \] constant of internal [dimensionless]
\[ g \] Earth acceleration [9,806 m²/s]

Values for \( n_{\text{flood}} \):

\[ \frac{\dot{L}}{\dot{V}} \sqrt{\frac{\rho_g}{\rho_l}} \leq 0,4 \quad n_{\text{flood}} = -0,326 \]

\[ \frac{\dot{L}}{\dot{V}} \sqrt{\frac{\rho_g}{\rho_l}} > 0,4 \quad n_{\text{flood}} = -0,723 \]

Calculation of gas velocity at flooding point

\[ w_{g,\text{flood}} = \left( \frac{g}{\varepsilon_{\text{flood}} a^{1/2}} \left( \frac{12 \eta_l}{\rho_l w_l} \right)^{1/2} \left( \frac{12 \eta_l}{\rho_l w_l} \right)^{1/3} \right) \sqrt{\frac{\rho_l}{\rho_g}} \] (65)

with

\[ \varepsilon \] voids fraction [m³/m³]
\[ a \] geometric surface [m²/m³]
\[ w_l \] velocity of the liquid phase [m/s]

Calculation of the velocity of the liquid phase

\[ w_l = \frac{\dot{L}}{\dot{V}} \sqrt{\frac{\rho_g}{\rho_l}} = \frac{\dot{L}}{\dot{V}} \frac{\rho_g}{\rho_l} \] (66)

Solving of equations 65 and 66 has to be done iteratively.

Calculation of the column area and the column diameter

\[ A_K = \frac{\dot{V}}{w_g \rho_g} \] (67)

\[ d_K = \sqrt{\frac{A_K}{\pi}} \] (68)
with

\[ \dot{V} \quad \text{mass flow of the vapour phase [kg/s]} \]

\[ w_g \quad \text{velocity of the vapour phase [m/s]} \]

\[ \rho_g \quad \text{density of the vapour phase [kg/m}^3] \]
4. Columns with Structured Packings

To intensify the mass transfer for thermal separation of gas liquid mixtures structured packings are used since early sixties. Packings enable good separation efficiencies at high loadings with low pressure drop. Based on the regular structure the problems of the randomize internals could be overcome. Even with low liquid loadings good separation efficiency is available. Based on the low pressure drop packings are used for vacuum distillation of temperature sensitive compounds and for separation with high numbers of theoretical steps.

Different types of structures packings are available:

- impulse packing
- tissue packing
- metal and plate packing
- skeletal packing

The impulse packing exists of single elements which are connected to larger units. The flow velocity of the gas phase is influenced by different cross sections.

The tissue packing is the simplest form existing of metal stripes which are rolled to a cylindrical form. Depending on the mesh size very high geometrical surfaces with high voids fraction can be produced. The well known design exists of flat and folded metal or plastic stripes. These stripes are connected in that form that open and crossing channels are produced, which have a certain angle to the column axis. For columns up to 1.5 m in diameters these packings are produced as cylinders which are inserted into the column. For columns of larger diameter the packings are produced as segments, which are connected in the column.

The metal and plate packings have the same construction as the tissue packings but instead of stripes folded and drilled metal or plastic plates are used. The construction in cylindrical or segment form depends again on the column diameter. This packings type can be designed also as thin wall ceramic.

The skeletal packings are plastic cubes with grid form structure.

For wire netting packings capillary effect arise, which guarantees for low liquid loadings an optimal distribution of the liquid and thus higher separation efficiencies. Because of the high dependency of these packings on the liquid loading this high separation efficiency can only be reached for low liquid loadings. With increasing liquid loading the separation efficiency decreases.

Although structured packings have a high surface per volume the liquid loading is only slightly higher than of randomize internals.
Further advantages of structured packings in comparison with the randomize packings are:

- no male distribution which means no wall effect of the liquid
- high specific surface of the packing
- beneficial flow form
- self distribution of the liquid
- strong balancing effect in the vapour phase
- complete and regular wetting of the surface and always renewing of the liquid film

4.1. Selection of Packing

Beside the hydraulic data the selection of the packing depends on stability for corrosion and temperature. Further a chemical inert behaviour for the mixture to be separated is necessary. The packing should have a good wetting characteristic and a low pollution sensitivity.

Depending on the application packings are produced in metal, plastic, graphite or ceramic material. For high corrosive mixtures packings in borosilicate glass (DURAPACK®-Schott) are available.

For gas-liquid systems the capacity of structured packings is described by the maximum liquid loading and the pressure drop. For liquid-liquid systems (extraction) the dispersed phase part and the droplet diameters are the significant parameters.

4.2. Layout of a column with structured packings

The mass transfer characteristics of a structured packing is described by the number of theoretical steps depending on the operation conditions.

Capacity and maximum loading of the column with structured packings is described by a flow parameter \( \psi \) and a loading factor \( c_{g,\text{max}} \).

From the hydraulically data the flow parameter \( \psi \) is determined:

\[
\psi = \frac{\dot{L}}{G} \sqrt{\frac{\rho_g}{\rho_l}}
\]  

(69)

with

- \( \dot{L} \) ......liquid flow [kg/h]
- \( G \) ......gas flow [kg/h]
- \( \rho_g \) ......density of the gas phase [kg/m³]
- \( \rho_l \) ......density of the liquid phase [kg/m³]
For determination of the loading factor $c_g$ [m/s] following calculation is necessary:

$$
c_g = w_g \sqrt{\frac{\rho_g}{\rho_l - \rho_g}} = F\text{-Faktor} \sqrt{\frac{\rho_l}{\rho_l - \rho_g}}
$$

(70)

with calculation of the $F$-factor:

$$
F\text{-Faktor} = w_s \sqrt{\rho_g} = 0,002533g \sqrt{\frac{T}{M_p}}
$$

(71)

with

- $M$ ....... molecular weight of the vapour phase [kg/kmol]
- $\rho$ ....... operation pressure [mbar]
- $T$ ......... operation temperature [K]
- $w_g$ ...... gas velocity in the empty column [m/s]

The maximum loading factor can be determined by a loading diagram.

Changing the type of packing the loading factor is corrected with a correcting factor $C$. This kind of packing is chosen, where the $C$-value is 20% higher than the calculated one. These corrections are given by the producer or can be calculated by following equation:

$$
C = \frac{c_g}{c_{g,max}}
$$

(72)

### Abb. 41: Maximum loading factor depending on the flow parameter

For the column area $A_k$ results:

$$
A_k = \frac{\dot{G}}{g} = \frac{\dot{G}}{3600 \cdot \frac{w_g}{c_g} \sqrt{\rho_g \left(\rho_l - \rho_g\right)}}
$$

(73)

with

- $\dot{G}$ ...... gas flow [kg/h]
- $g$ ...... Earth acceleration [9,81 m/s$^2$]
and for the column diameter $d_K$

$$d_K = \sqrt[4]{\frac{4}{\pi} A_K} = 1,13 \sqrt{A_K}$$  \hfill (74)

For the praxis 75 - 80% of the value $c_{g,\text{max}}$ is chosen.

For changing an existing column a different kind of calculation has to be done. From the existing column diameter and the gas loading the loading factor is calculated:

$$c_g = \frac{\dot{G}}{A_k \sqrt{\rho_g (\rho_l - \rho_g)}}$$  \hfill (75)

These calculations are valid within following boundaries:

- viscosity of the liquid < 2 cP
- pressure < 2 bar

Abb. 42: Flow sheet for calculation of the column diameter
4.3. Description of packings used in industry

SULZER COMPANY

Mellapack®

Made in metal or plastic and usable for large areas of liquid loadings. A changing installation of the single angled blades gives open crossing channels, which result in optimal mixing of the flows. The angle of the channels is alternative 30° and 45°.

Metal Tissue packing BX® and CY®

This kind of packing is used for high numbers of separation steps.

Further characteristics are:
- low hold-up
- usable for low column heights
- useable for large operation areas

Not usable are tissue packings for polluting systems and for non wetting liquids.

Tissue packing in plastic

The limit of plastic packings is for temperature areas of 80° to 100°C. So these packings are used mainly for absorption columns, where a large operation area is available.

Mellacarbon®

Carbon has an inert chemical behaviour for most solvents, acids and bases. Also high thermal treatment of > 400°C is possible.

Melladur®

This structured packing is produced in chemical technical porcelain, which can be used for extremely high temperatures (T > 1000°C). Further the corrosion resistance is extremely good.
GERMANIA COMPANY

Perform-Grid Packings

Perform-Grid packings are produced from roof form metals and part of the material sticks out from the geometrical form of the ground material so that additional free areas for the flowing phases exist. The single elements are mounted this way that the orientation of the channels changes from element to element.

The Perform-Grid packing is used for separation problems with high loadings and can be uses as well for high gas as for high liquid loading.

KÜHNI COMPANY

Kühni-Rombopak

Kühni-Rombopak is produced from thin riffled metal follies.

Characteristics of this packing are:

♦ high separation efficiency at low pressure and low vapour loading
♦ low pressure drop
♦ large working area

MONTZ COMPANY

Fine tissue packings are produced from thin wires of 0,2 to 0,3 mm. This kind of packing is used preferable for vacuum distillation.

SCHOTT COMPANY

Durapack

Durapack-packings exist of riffled glass plates with channels fort he flows of 45° angle. The surface of these packings can be smooth or rough. Rough surfaces result in a better wetting of the surface and are used for distillation and absorption. The advantages of glass are surfaces without pores, the catalytic inert behaviour and the inflammable material. Without the prose no swelling of the packing is available which might be a problem with plastic packings.