Staged column design

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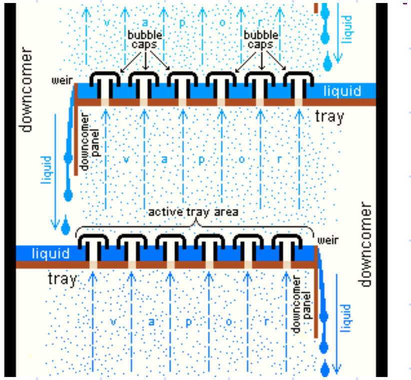


Agenda

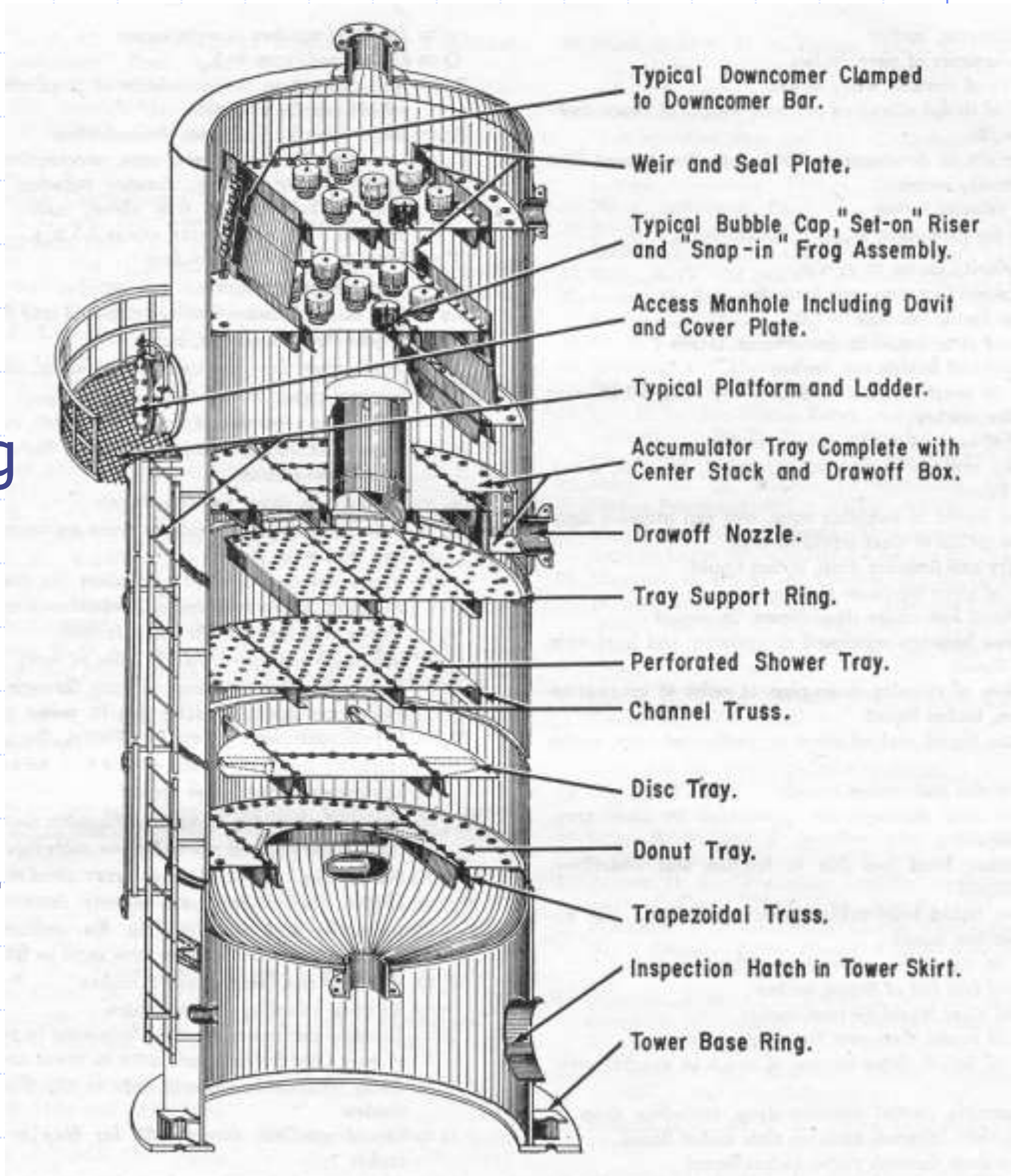
- Stage column internals: terminology
- Trays geometries
- Column hydrodynamics: flooding, weeping, loading
- Tray efficiency
- Pressure drops calculation
- Fair method for flooding velocity
- Design and rating of perforated trays
- General design criteria

Overall Column Design Goals

- Maximize separation
- Minimize manufacturing and installation cost
- Minimize energy operating cost
- Minimize maintenance cost
- Provide operating flexibility

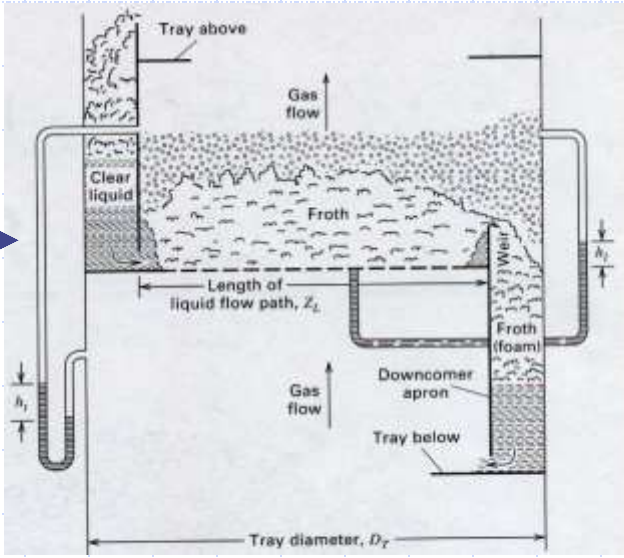
Staged Column Internals – Terminology

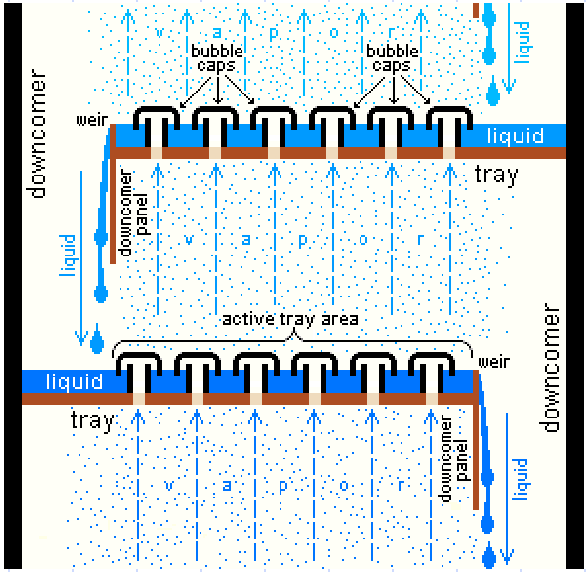
- Tray – a horizontal plate which supports the vapor-liquid mixture and serves as an equilibrium stage.
- Downcomer – an opening in the tray which allows the liquid to flow down the column.
- Weir – a vertical plate or “dam” at the downcomer to provide a given vapor-liquid mixture depth on the tray.



Tray Design

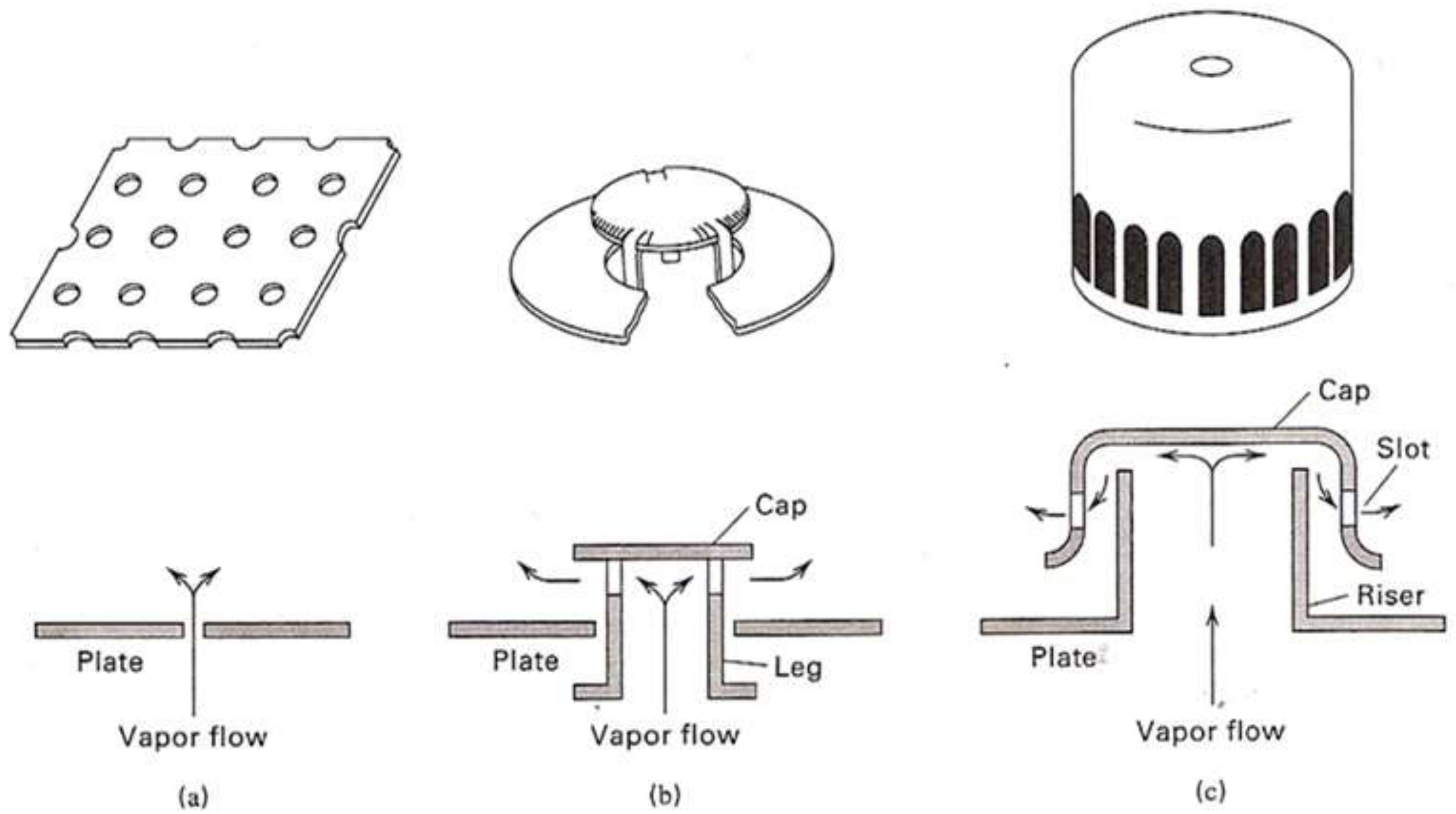
- Tray types
  - Sieve or Perforated – simply a tray with vapor holes
  - Bubble Cap – a cap placed over the tray's vapor holes
  - Valve – a valve placed over the tray's vapor holes
- Try design goals: maximize column efficiency
  - Enhance vapor-liquid mixing
  - Maintain optimum vapor flow
  - Maintain optimum liquid depth
  - Minimize pressure drop
  - Prevent fouling



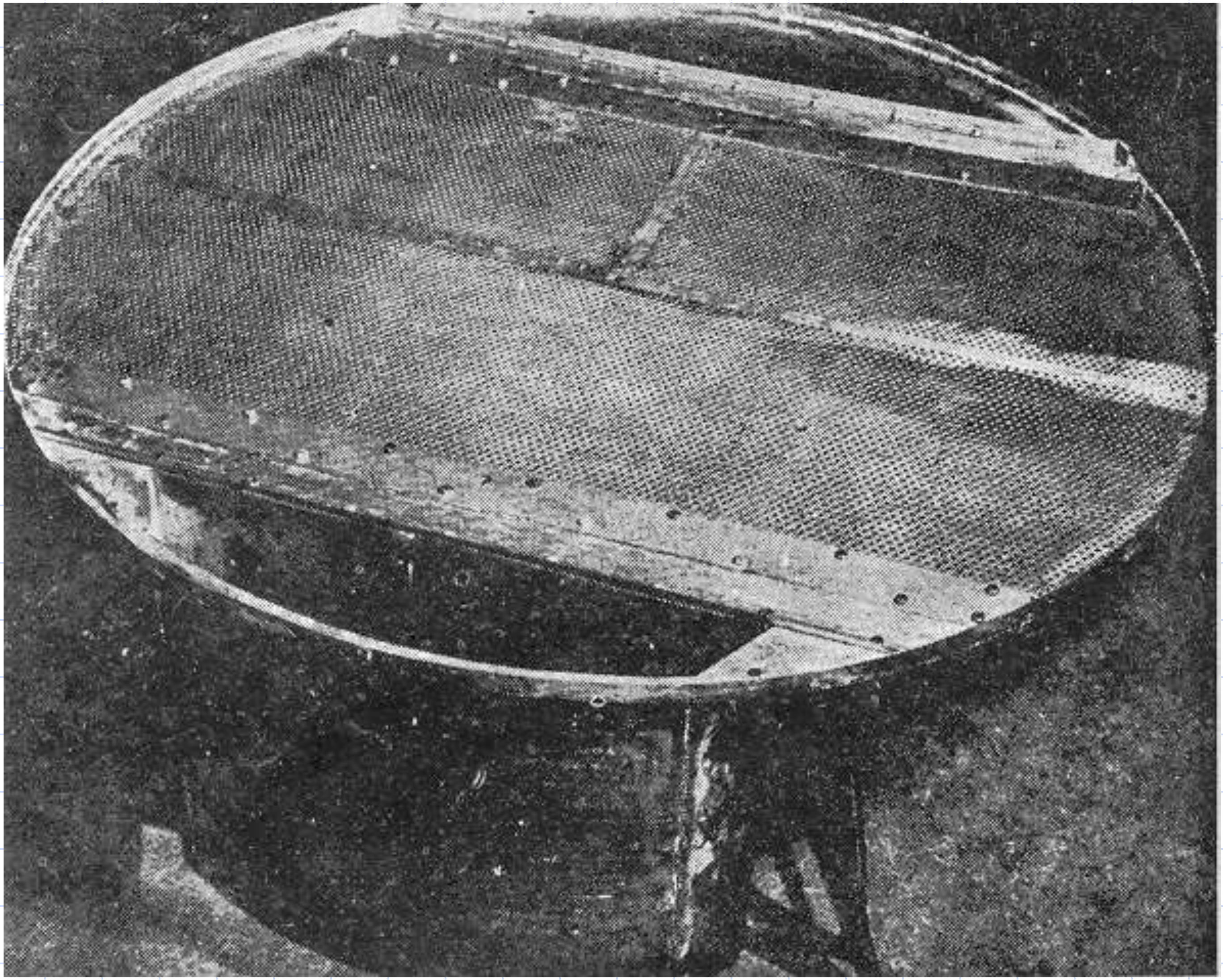


Different trays

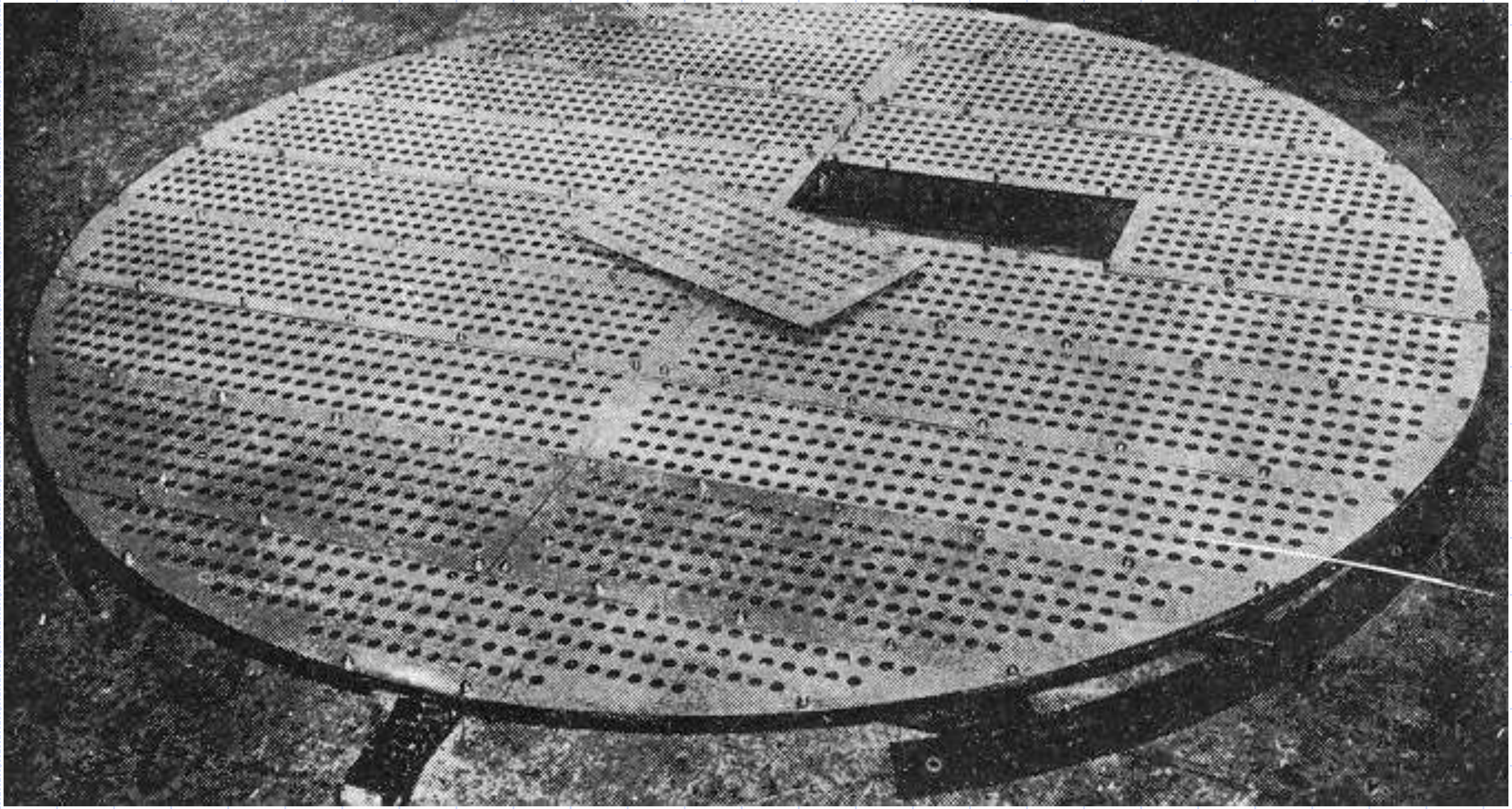
Perforated tray | Valve tray | Bells tray



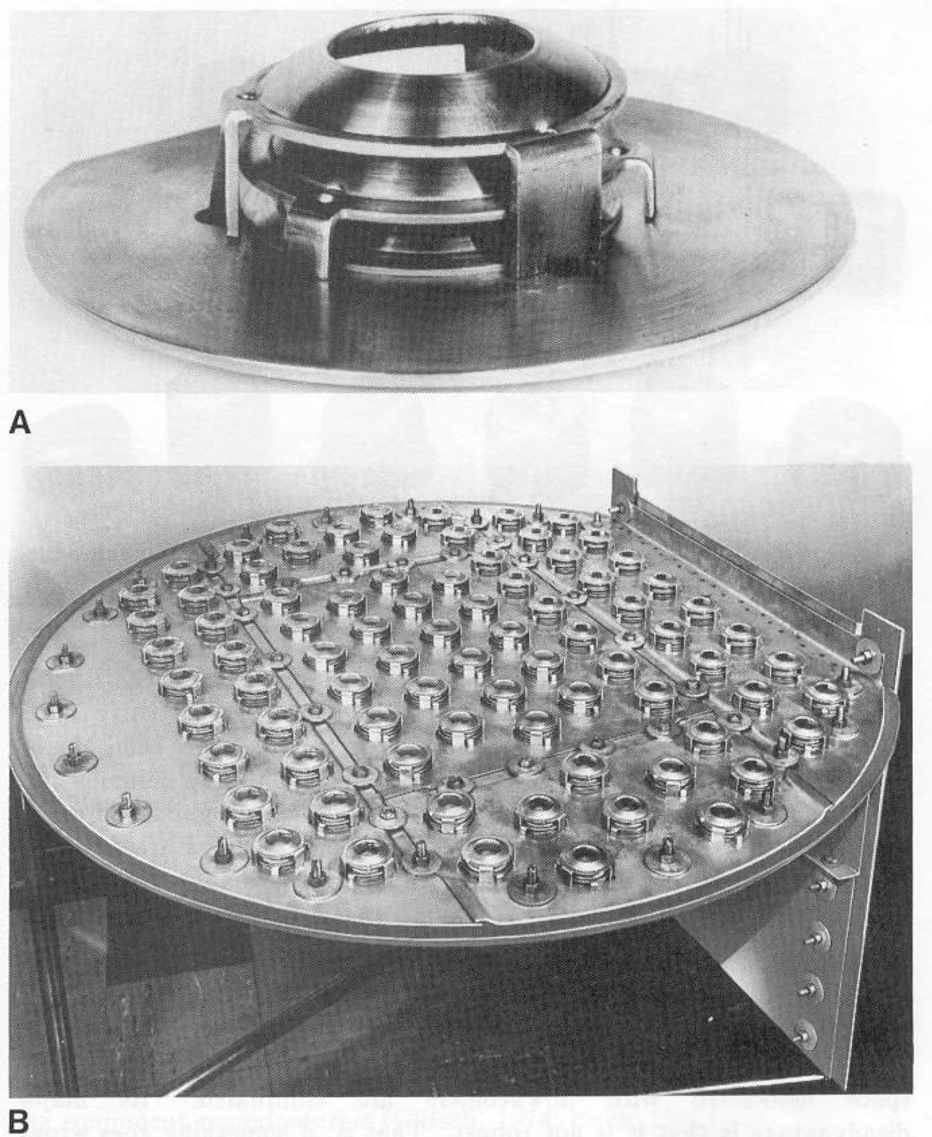
Sieve Tray



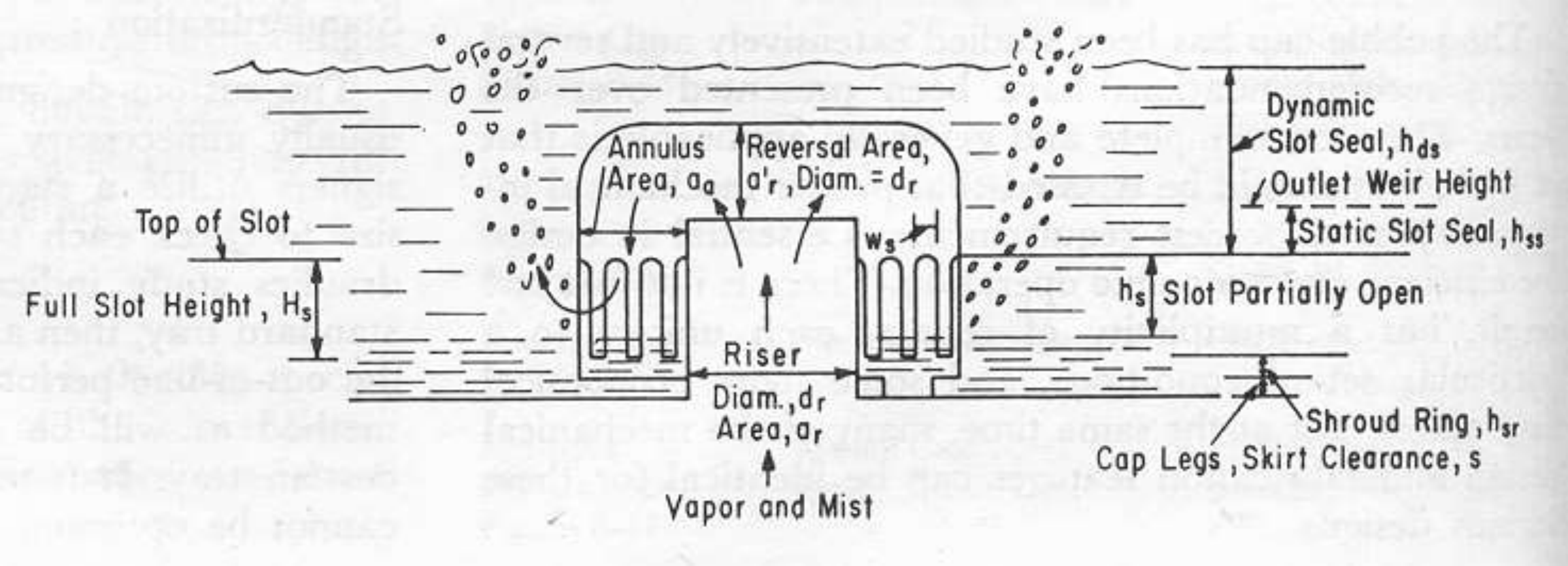
Perforated Tray



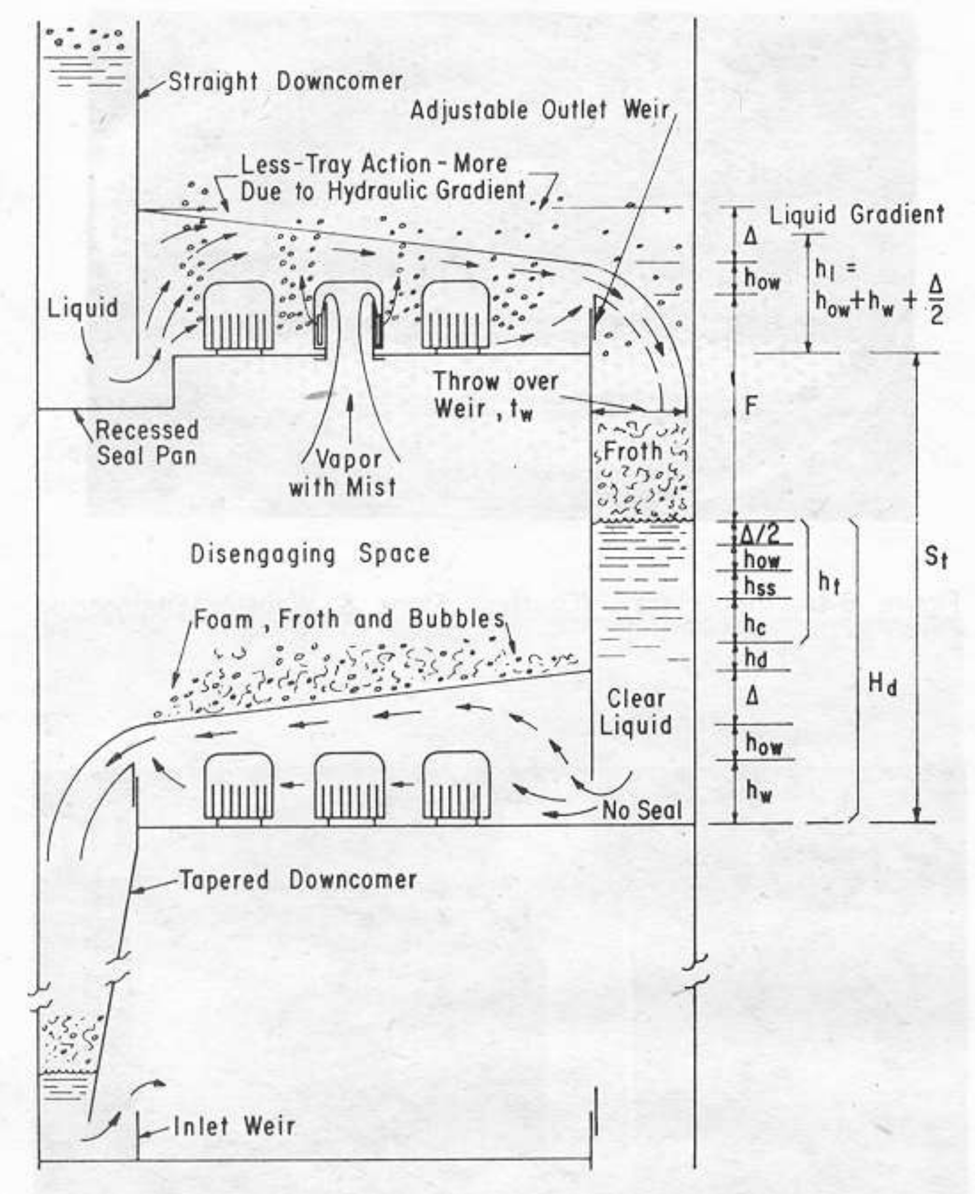
Valve and Valve Tray



Bubble Cap Close Up



Vapor/Liquid Flow Paths



Vapor Flow Path

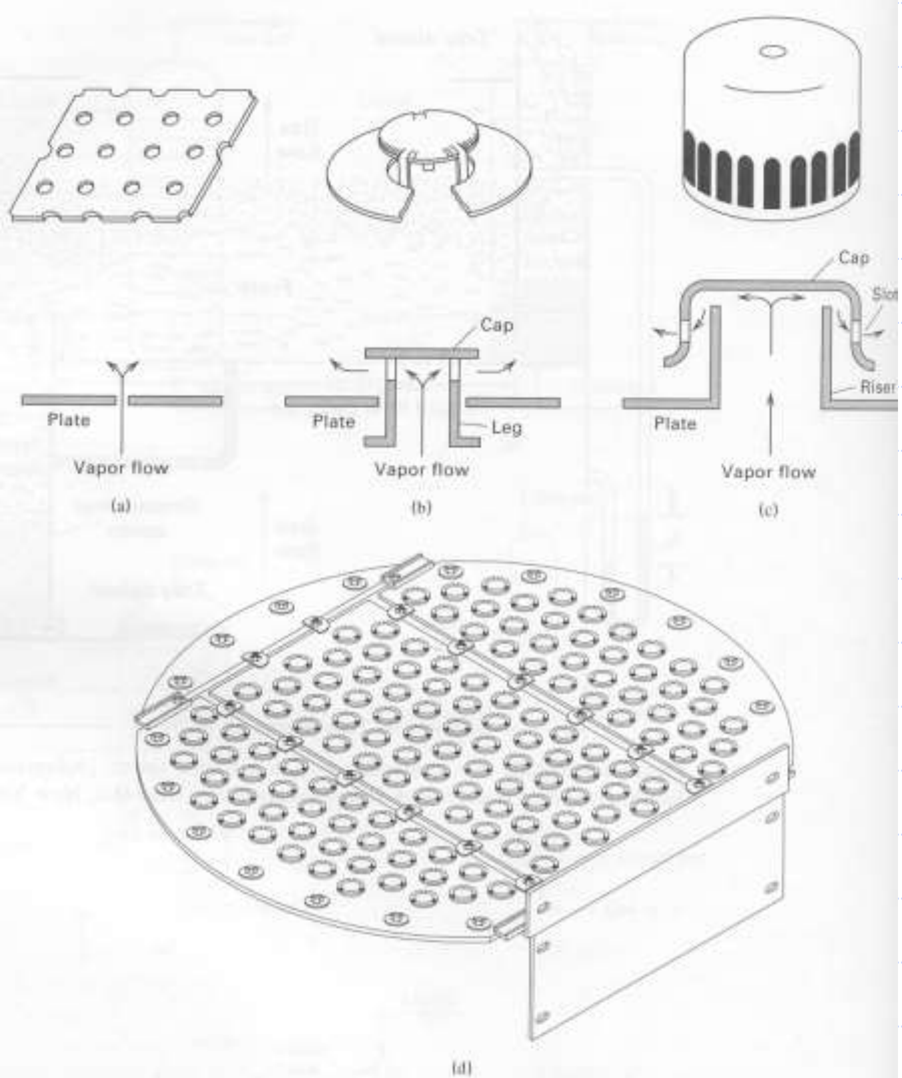
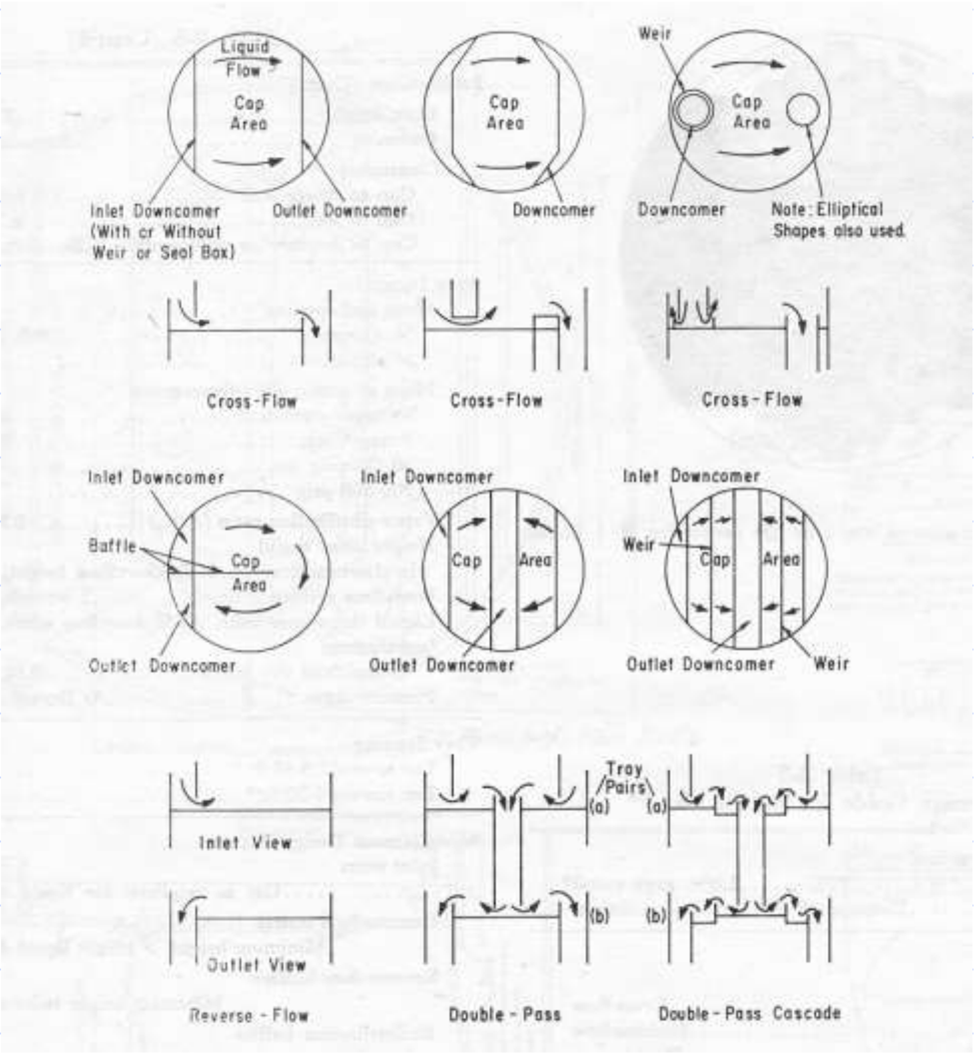


Figure 6.5 Three types of tray openings for passage of vapor up into liquid: (a) perforation (b) valve cap; (c) bubble cap. (d) Tray with valve caps.

Liquid Flow Paths – Passes



Two-Phase Transport Dependencies

- Liquid
  - Liquid-phase mixing (fluid dynamics)
  - Liquid-phase droplet size and size distribution (surface tension)
  - Liquid-phase mass transport properties (diffusivity)
- Vapor
  - Gas-phase mixing (fluid dynamics)
  - Gas-phase bubble coalescence and breakup (stability)
  - Gas-phase bubble rise velocity (density)
  - Gas-phase bubble size and size distribution (surface tension)
  - Gas-phase transport properties (diffusivity)
- Liquid-Vapor
  - Gas-liquid-phase interfacial area (contact area)
  - Gas-liquid-phase interfacial mass transport properties (solubility)
- Note that all of these properties – as well as other transport properties, e.g., thermal – interact to yield the overall system behavior

Vapor-Liquid Flow Regimes

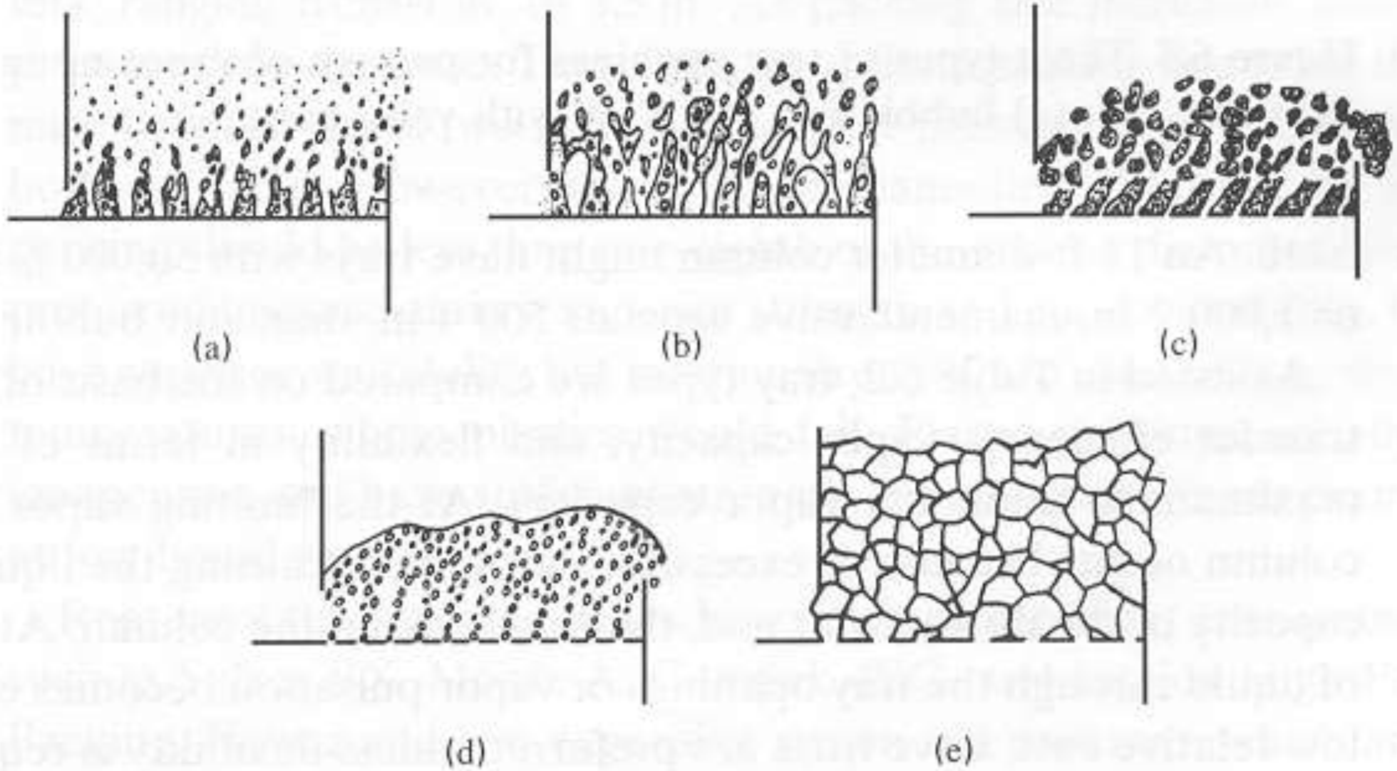


Figure 6.4 Possible vapor–liquid flow regimes for a contacting tray: (a) spray; (b) froth; (c) emulsion; (d) bubble; (e) cellular foam. [Reproduced by permission from M.J. Lockett, *Distillation Tray Fundamentals*, Cambridge University Press, London (1986).]

Flow Regimes

- Bubble Regime
  - Occurs at low gas flow rates
  - Distinct vapor bubbles rising through continuous liquid phase
  - Poor mixing and liquid-vapor contact
  - Low efficiency
- Froth Regime
  - Occurs at medium gas flow rates
  - Liquid phase is continuous with large, pulsating vapor voids
  - Liquid phase is well mixed and vapor is not
  - High efficiency for liquid-phase, mass-transfer limited system
  - Most common regime for operation

Flow Regimes

- Spray Regime
  - Occurs at high vapor flow rates and low liquid depths (low weir)
  - Vapor phase is continuous and liquid forms small droplets
  - Vapor is well mixed and liquid is not
  - Low efficiency for liquid-phase, mass-transfer limited system
- Emulsion Regime
  - Occurs at high liquid rates
  - Vapor-phase bubbles emulsify
  - Liquid phase is not well mixed
  - Low efficiency for liquid-phase, mass-transfer limited system
  - High efficiency for vapor-phase, mass-transfer limited system
- Foam Regime
  - Occurs at low to medium flow rates where vapor bubble coalescence (a property of the components) is hindered
  - Liquid phase is continuous while large vapor bubbles form
  - High efficiency for vapor-liquid-phase, mass-transfer limited systems
  - Leads to entrainment of liquid between stages

What to Avoid in the Column – Flooding, Weeping and Foaming

- Flooding occurs at high vapor flow rates – excessive entrainment of liquid overcomes the downcomer capacity and the column floods – or large liquid flow rates.
- Weeping occurs at low vapor flow rates – liquid flows or pulses back through the tray vapor openings.
- Foaming occurs when the components form a stable foam – efficiency of the column drops and the column may flood.

Overall Efficiency

- The overall efficiency is defined as

$$E_o = N_{equil} / N_{actual}$$

- The vapor flow rate affects the column operating parameters including entrainment, flooding, weeping and the flow regime;
  - thus, in many systems, the overall efficiency is a strong function of vapor flow rate
- It depends on mass transfer, liquid entrainment, ...
- Different methods, rough estimation anyway (average error: ± 30%)
- examples: AIChE method, o'Connor plots,...

Operating Ranges – Vapor vs. Liquid Flow Rates

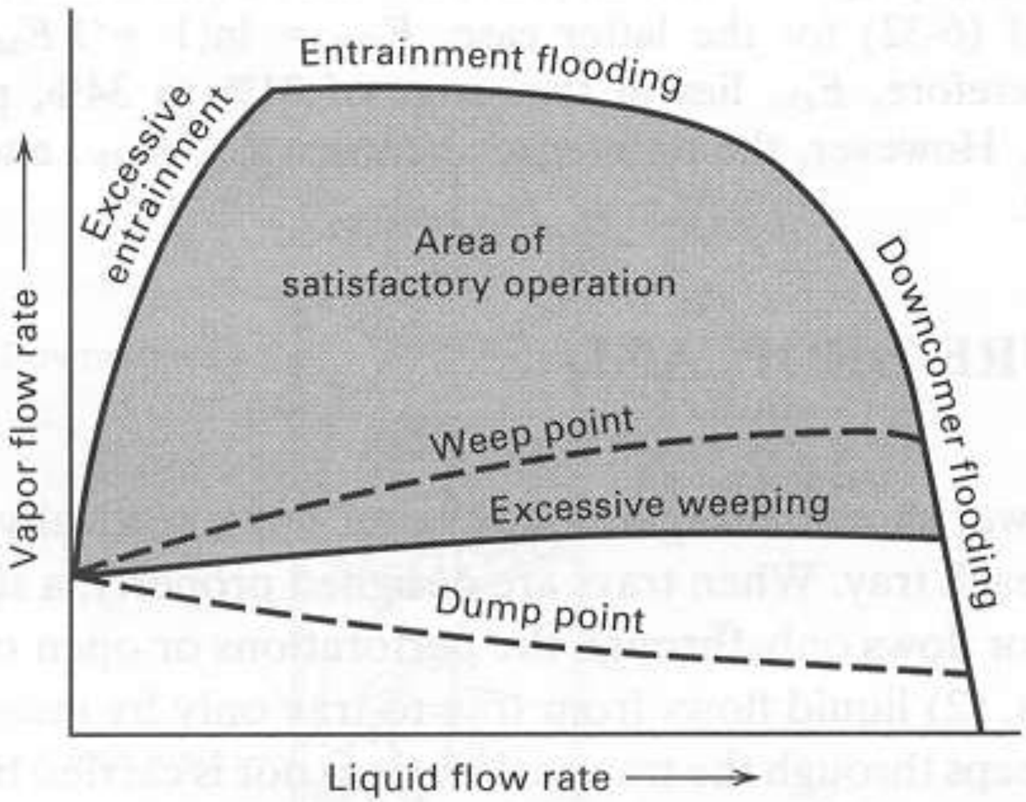


Figure 6.22 Limits of stable operation in a trayed tower. [Reproduced by permission from H.Z. Kister, *Distillation Design*, McGraw-Hill, New York (1992).]

Operating Ranges – Efficiency vs. Vapor Flow Rate

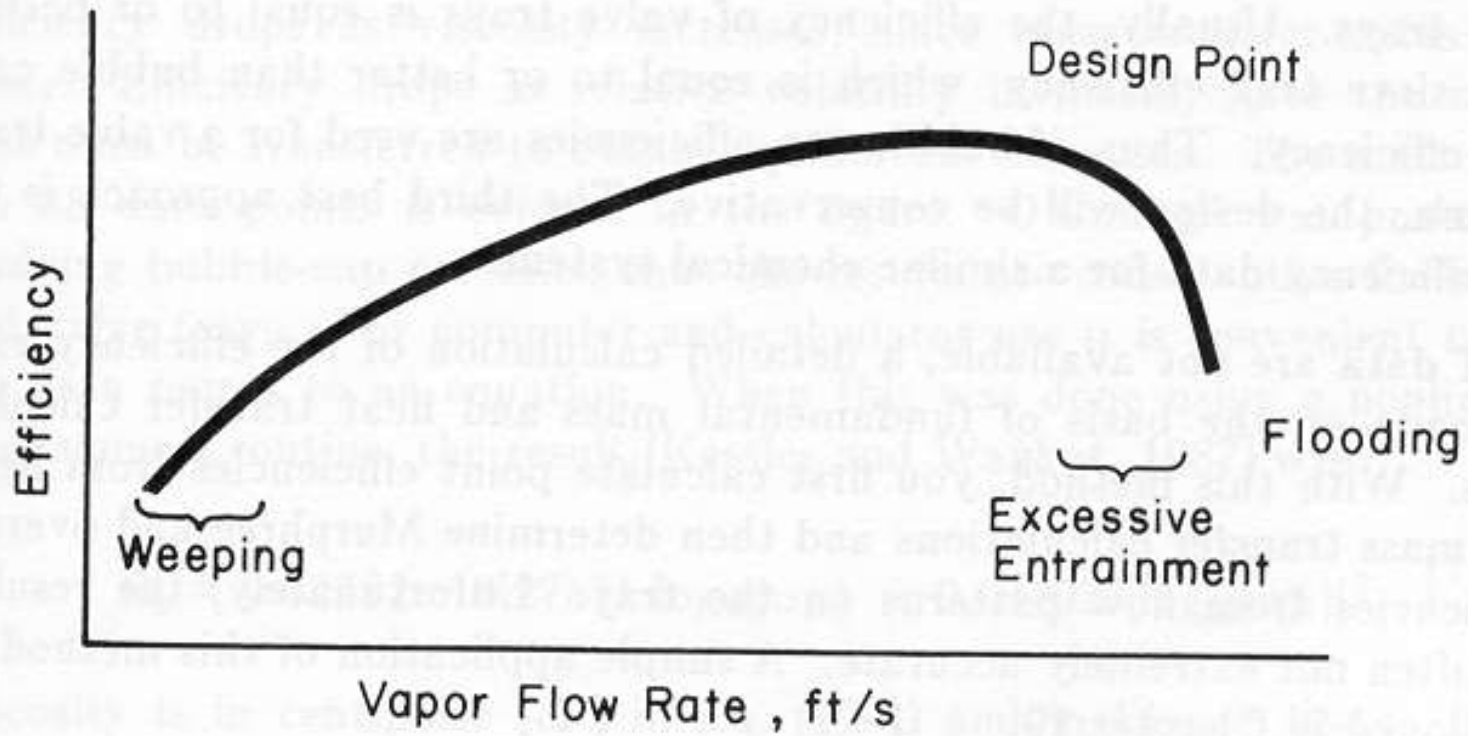
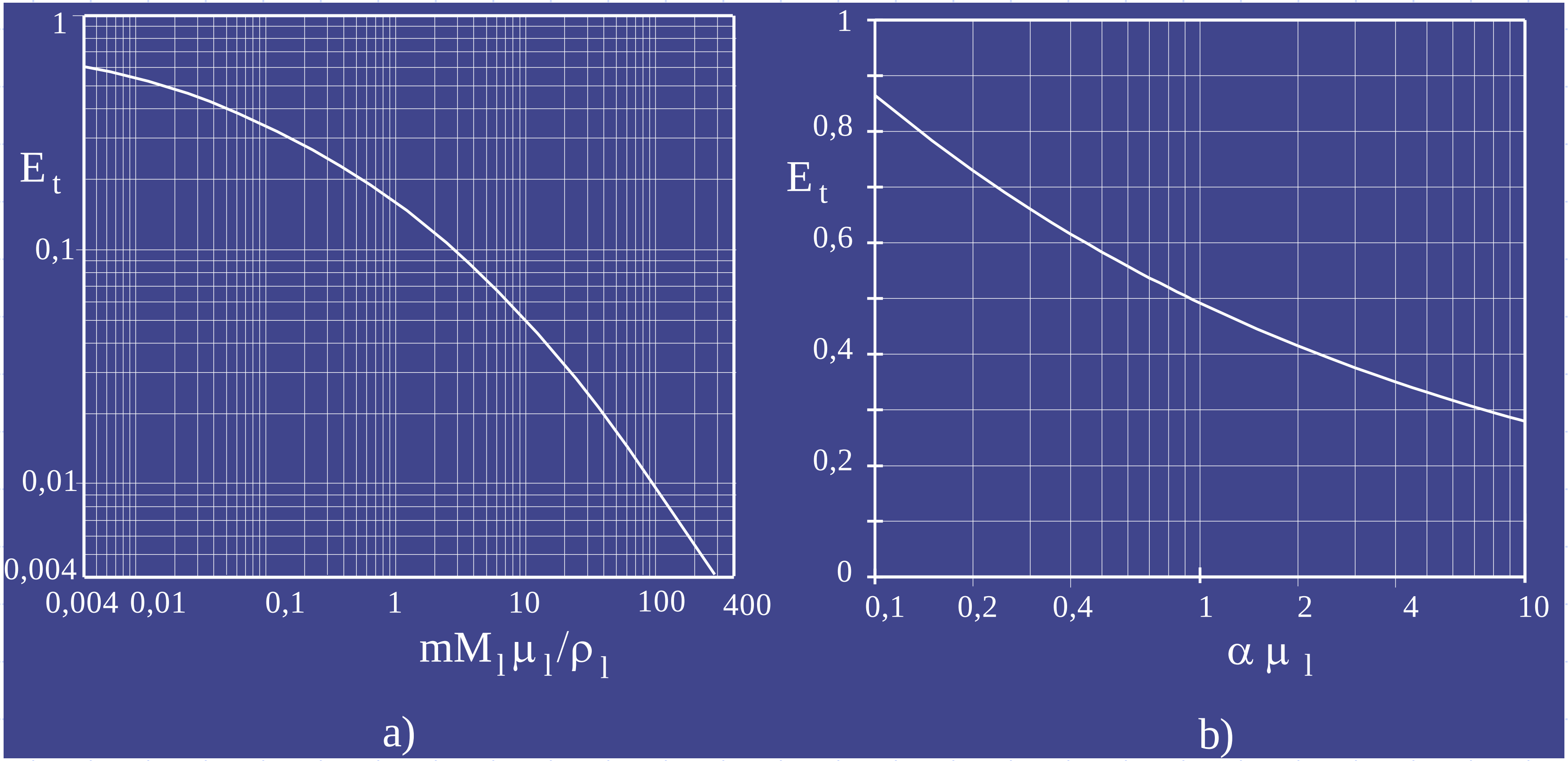


Figure 12-13. Efficiency as a function of vapor velocity.

Tray Efficiency

- Estimated from empirical correlation in graphical form



Tray Efficiency

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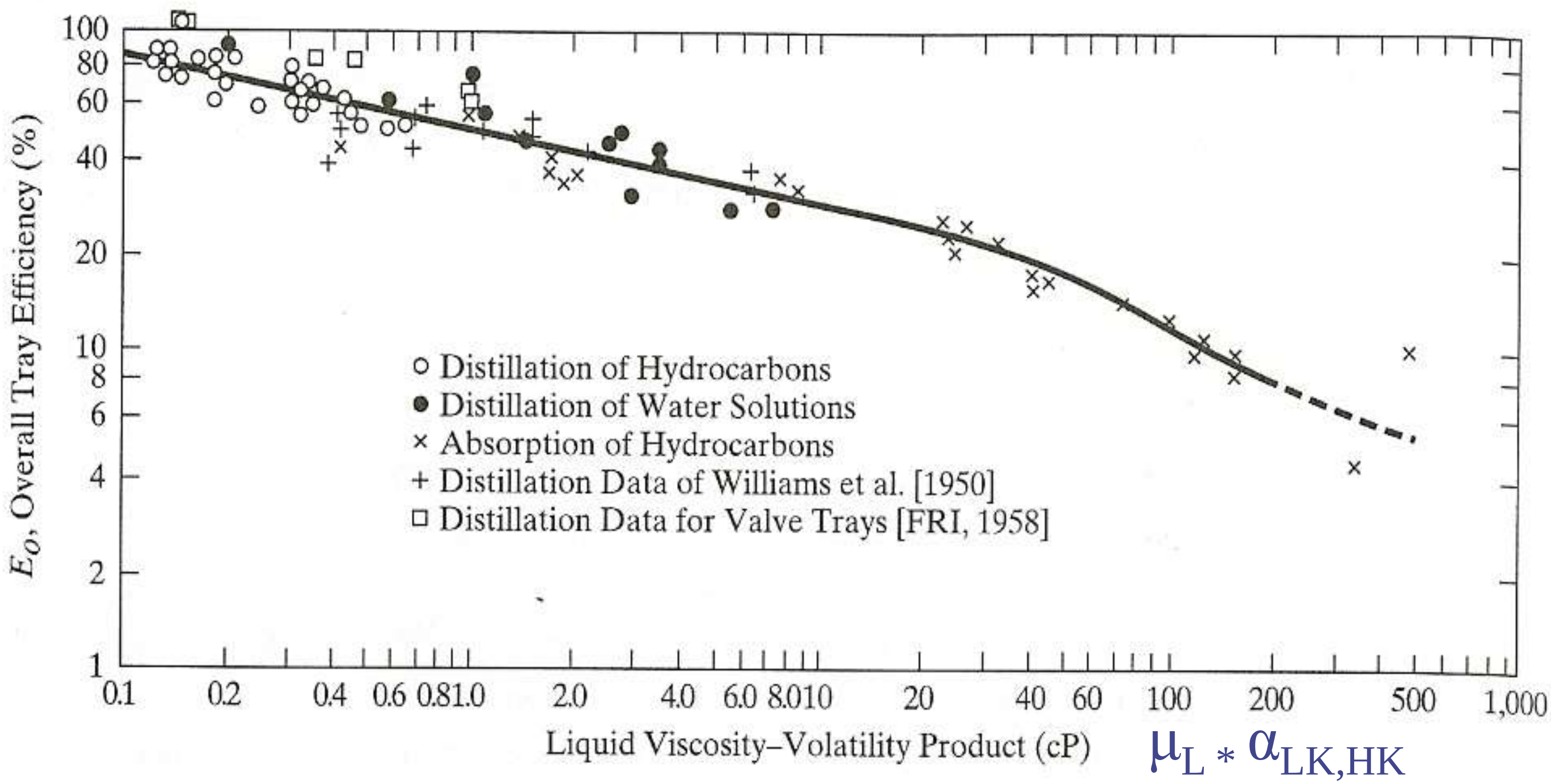


Lockhart and Leggett version of O'Connell correlation for plate efficiency.

Example: overall efficiency estimation

- A sieve-plate distillation column is separating a feed that is 50 mole % n-hexane and 50 mole % nheptane. Feed is a saturated liquid. Plate spacing is 24 in. Average column pressure is 1 atm. Distillate composition is xD = 0.999 (mole fraction n-hexane) and xB = 0.001. Feed rate is 1000 lbmol/h. Internal reflux ratio L/V = 0.8. The column has a total reboiler and a total condenser. Estimate the overall efficiency.
- Equilibrium data:

x_{C6}	0	0.341	0.398	0.50	1.0
y_{C6}	0	0.545	0.609	0.70	1.0
T, °C	98.4	85	83.7	80	69

Example: overall efficiency estimation

- Relative volatility is $\alpha = (y/x)/[(1-y)/(1-x)]$. The average temperature can be estimated several ways:
  - Arithmetic average $T = (98.4 + 69)/2 = 83.7$, $\alpha = 2.36$
  - Average at $x = 0.5$, $T = 80$, $\alpha = 2.33$
  - Not much difference. Use $\alpha = 2.35$ corresponding to approximately 82.5°C.
- The liquid viscosity of the feed can be estimated from
  - $\ln \mu_{mix} = x_1 \ln \mu_1 + x_2 \ln \mu_2$
  - Pure component viscosities can be estimated from $\log_{10} \mu = A(1/T - 1/B)$
  - where μ is in cP and T is in kelvins
  - nC6: $A = 362.79$, $B = 207.08$
  - nC7: $A = 436.73$, $B = 232.53$
  - These equations give $\mu_{C6} = 0.186$, $\mu_{C7} = 0.224$, and $\mu_{mix} = 0.204$.
  - Then $\alpha\, \mu_{mix} = 0.480$. From O'Connell plot, $E_O = 0.59$.
  - Note that once T_{avg}, α_{avg}, and μ_{feed} are estimated, calculating EO is easy.

Staged column sizing

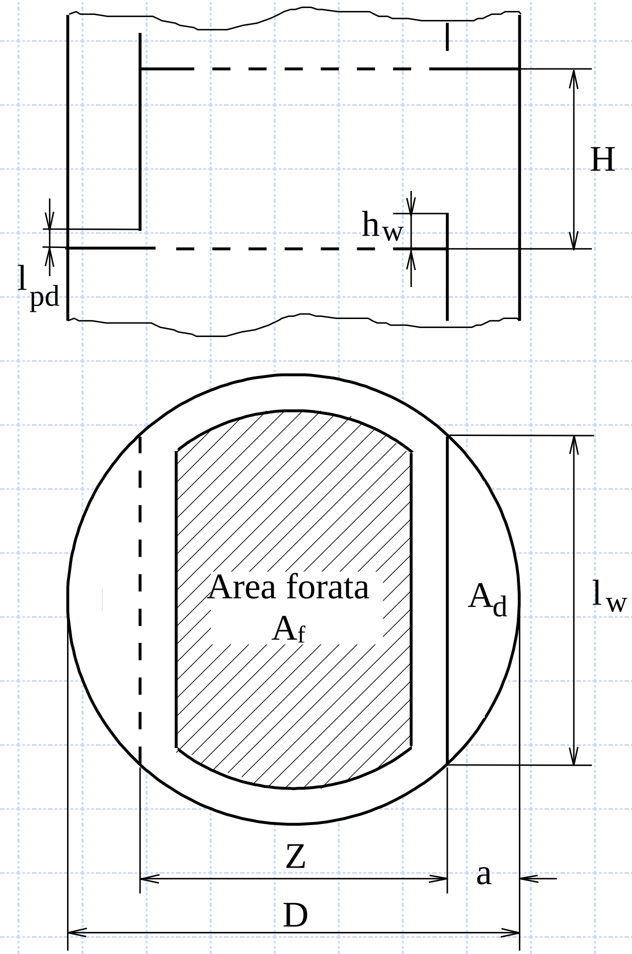
- Sizing means determining:
  - Height (Z)
  - Diameter (D)
- Height is calculated by the following expression

$$Z = \left(N_{stages} - 1\right)H + Z_{bottom} + Z_{top}$$

- Where:
  - $H =$ *tray spacing*
  - Z_{bottom} = top height (~ 2-3 m)
  - Z_{top} = bottom height (~ 1 m)
- $H = H(D)$, therefore the most important procedure is the calculation of D

Perforated tray geometry

- Elements:
  - D = column diameter
  - H = tray distance
  - d = downcomer
  - h_w = weir height
  - l_w = weir length
  - l_{pd} = length of downcomer
- Areas:
  - A_t = total area of the column section;
  - A_f = perforated area;
  - A_h = area of the holes;
  - A_d = area of the downcomer;
  - A_n = net area = A_t - A_d;
  - A_a = active area = A_t - $2A_d$



Design and verification of perforated trays

- The main variables for design / rating is the **vapor velocity** which is calculated referring to the net area:

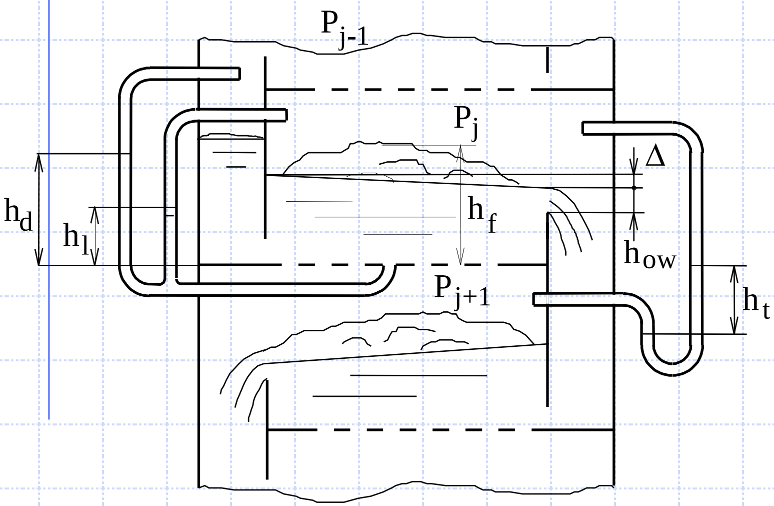
$$u_n = \frac{V_v}{A_n} \; with \; u_n = 1 - 2 \; m/s$$

- In design mode
  - Known V_v
  - Calculate u_n (Fair method) $u_n = K_5 u_{n,fl}$
  - Calculate A_n
  - Calculate A_t
  - Calculate D $D = \sqrt{\frac{4A_t}{\pi}}$

- In rating mode (1)
  - Known A_n, V_v
  - Calculate u_n (Fair method) $u_n = V_v / A_n$
  - Calculate K_5

- In rating mode (2)
  - Known A_n, K_5 is fixed
  - Calculate A_t
  - Calculate u_n $u_n = K_5 u_{n,fl}$
  - Calculate $V_v = u_n A_n$

Pressure drops



Definitions:

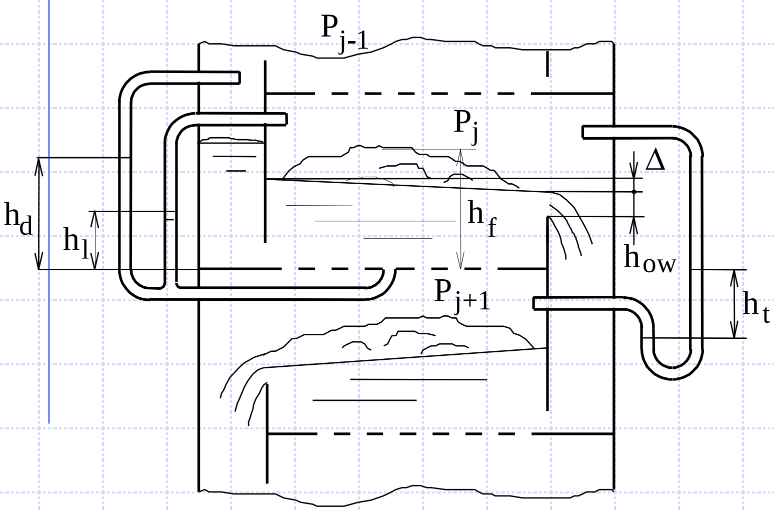
- h_l = height of clear liquid above the tray
- h_d = height of clear liquid in downcomer
- h_{ow} = height of clear liquid above the weir
- $P_{j+1} - P_j$ = total pressure drops for the tray
- h_t = total pressure drops in units of clear liquid

- Clear liquid is degassed liquid
  - In realty the liquid above the tray is a foam
- Density of the foam is defined, with respect to the density of the clear liquid:

$$\varphi = \frac{h_l}{h_f}$$

- The height of the liquid is called “liquid head”.

Pressure drops – pressure balance



$$\Delta P = P_{j+1} - P_j = \rho_l g h_t$$

$$P_j + \rho_l h_d g = P_{j+1} + \rho_l h_l g + \Delta P_{pd}$$

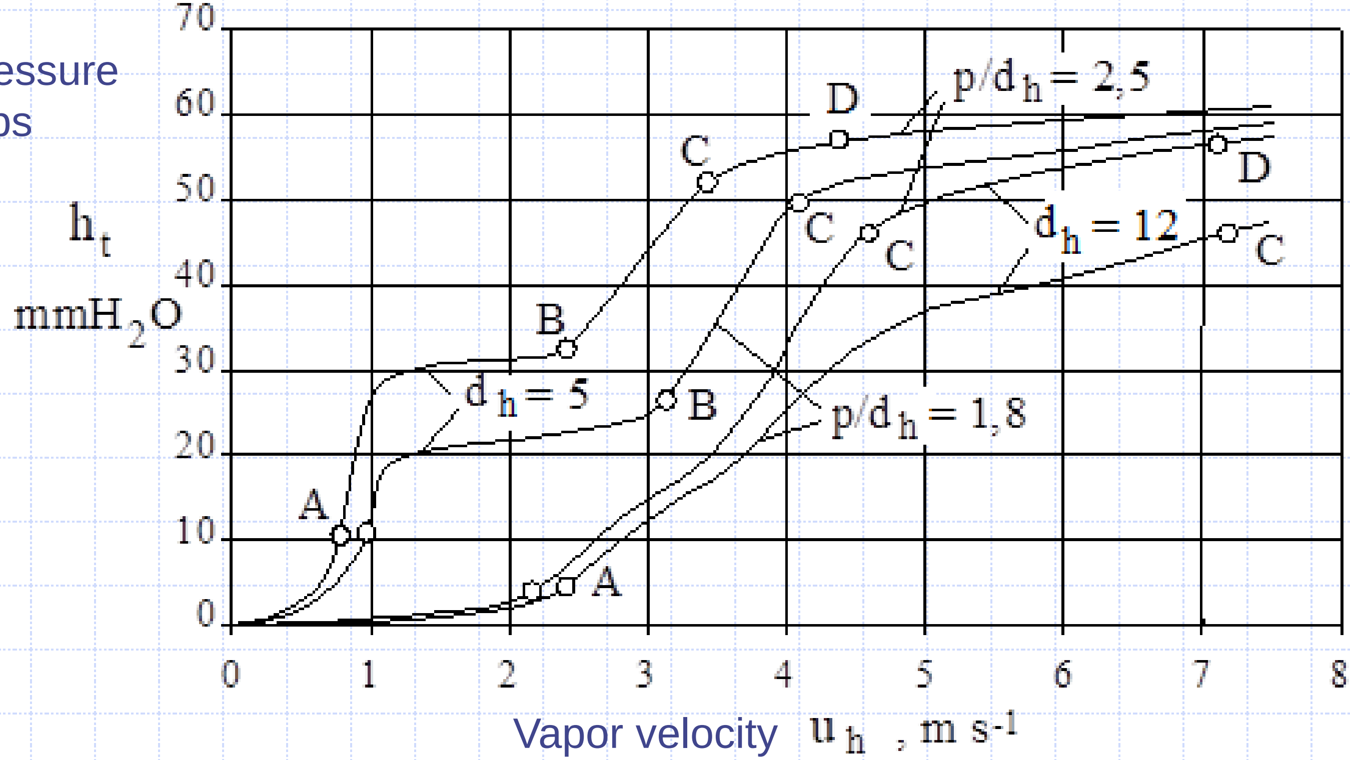
$$h_d = h_t + h_l + h_{pd}$$

- It is desired that: $h_d < 0.5H$
- When the vapor velocity increases, pressure drops increase and consequently h_t increases and the liquid level in downcomer goes up
- If it is too high, it reaches the tray above and the column is clogged i.e. the liquid cannot go down
- This situation is named FLOODING and must be avoided

Operative conditions of a perforated tray

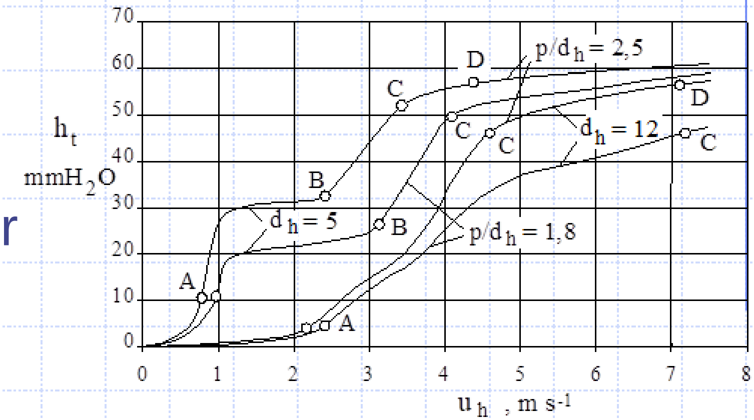
- In normal conditions a two phase L and V mixture is present over the tray with
  - Possible dragging of liquid to the upper tray
  - Possible liquid flow through the tray vapor openings
- For a correct operating condition liquid drip should be minimum respect to the total liquid flow

Total pressure drops



Effect of Holes dimension and ratio p/d on total pressure drops

Lower operative condition - LOADING



- For a raising vapor velocity (figure):
- Initially all the liquid flows down the first rows of vapor openings, while vapor goes up through the others: pressure drops goes up with a quadratic law until point A
- At a given time the liquid is distributed over the try: with large openings the vapor bubbles in a spray regime, while with narrow openings it bubbles only in some zones and the liquid flows down in other zones.
  - Pressure drops and liquid head goes up
- For further increase bubbling area gets bigger and pressure drops remain mostly constant (point B)
- Further increase of vapor velocity cause increase of liquid level up to the weir height (point C).
  - In this situation liquid head depends on vapor flow rate
- After point C raising u_h implies a decrease of liquid flow down the vapor openings and increase of liquid in downcomers.
- At point D dripping became negligible (e.g. <0.05L).

Upper operative condition - FLOODING

- Upper operating limit is the flooding:
- This situation starts in one or more trays (top or bottom) and extends to the other trays
  - It is characterized by high pressure drops and rapid efficiency decline
  - Vapor flow becomes irregular and liquid may exit from the top
- Flooding is the consequence of two phenomena:
  - High pressure drops due to entrainment of liquid (h_h increases since it depends on density of L-V mixture)
  - Cloggings in the downcomer due to the increased liquid flow or blockage of passage (due to solids) or reduced degassing of the mixture (high pressure systems with small density difference between L and V)
- These two phenomena are always associated and bring the column hydrodynamics out of equilibrium

Flooding velocity

- Flooding velocity $u_{n,fl}$ is a function of T,P, and composition
  - It must be evaluated on each tray
- It is possible to predict which is the most critical tray.
  - Anyway calculation must be done at least at the feed, top and bottom trays
- Column diameter depends on the tray having the lowest flooding velocity (larger diameter)
- In some cases (sub cooled feed) vapor flow rate in the stripping section is much higher than the one in the enriching section
  - It is then possible to build a column with two diameters to avoid having a too low vapor flow in the upper part to hold the liquid on the trays.
  - In general, $0.4 < K_5 < 0.8$.

Fair method for estimating flooding velocity

- Fair correlation aims at avoiding liquid dragging, which depends on the drops dimensions .
- Liquid entrainment is a function of the capacity factor K_n which is estimated by balance of forces around the drops.

$$K_n = u_n \sqrt{\frac{\rho_v}{\rho_l - \rho_v}}$$

- K_n is related to the flow parameter:

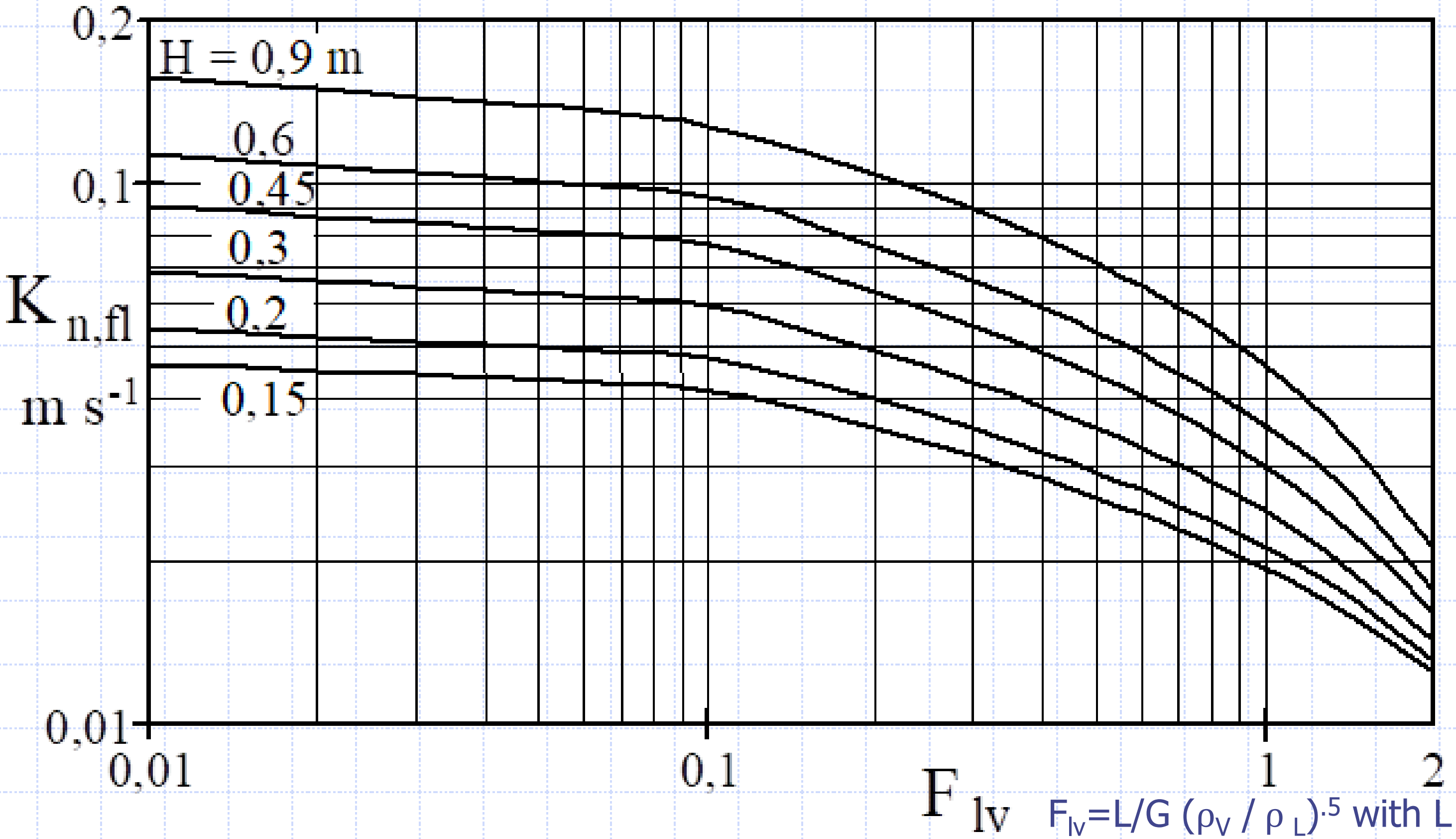
$$F_{lv} = \frac{L_v}{V_v} \sqrt{\frac{\rho_l}{\rho_v}}$$

  - L_v and V_v are volumetric flow rates
- Entrainment depends also on the distance between the liquid level and the tray above (i.e. the trays spacing H).
  - Since flooding corresponds to a given dragging value, it is possible to identify a limit value for the capacity factor as a function of F_{lv} and H

$$K_{n,fl} = f\left(F_{lv}, H\right)$$

Fair method for estimating flooding velocity

- This correlation is obtained from experimental data on existing columns and refer to non foaming systems with σ=20 dyne/cm, $h_w < 0.15H$, $A_h/A_a = 0.1$, $d_h < 6$mm



$F_{lv}=L/G\ (\rho_V / \rho_L)^{.5}$ with L and G in kmol/h

Calculation of flooding velocity

$$u_{n,fl} = K_{n,fl} K_1 K_2 K_3 K_4 \sqrt{\frac{\rho_l - \rho_v}{\rho_v}} \qquad u_n = K_5 u_{n,fl}$$

- K_1: related to surface tension.
  - For hydrocarbons it is σ = 20 dyne/cm
  - $K_1 = (\sigma/_{20})^{0.2}$
- K_2: related to try geometry A_h/A_a
  - $K_2 = \left(10\, {A_h}/_{A_a}\right)^{0.44}$ if $A_h/A_a < 0.1$; $K_2=1$ if $A_h/A_a >= 0.1$
- K_3: related to vapor openings: flooding velocity is reduced by 10% if openings diameter is large
  - $K_3 = 0.9$ for $d_h > 6$ mm; $K_3 = 1$ for $d_h < 6$ mm
- K_4 is an empirical factor related to foam formation

Design of a perforated tray column

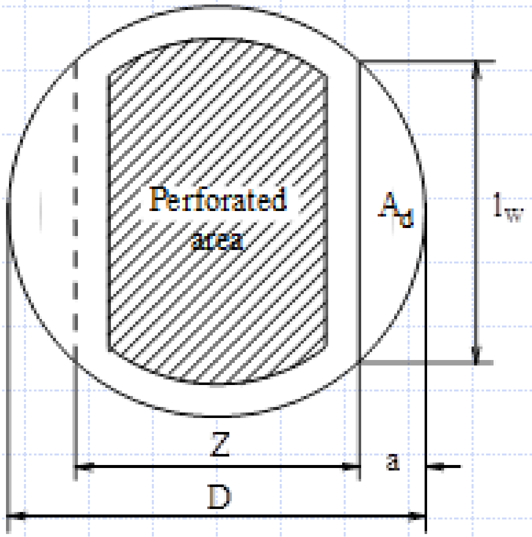
1. Start with an H initial value:
   - Define vapor velocity referring to the total tray area u_t=1-2 m/s
   - Calculate total area $A_t=V_v/u_t$ and then the diameter $D = \sqrt{4A_t/\pi}$
   - Calculate $H = 0.41\sqrt{D}$
2. Use Fair diagram to estimate $K_{n,fl}$
3. Estimate flooding velocity and net velocity according to

$$u_{n,fl} = K_{n,fl}K_1K_2K_3K_4\sqrt{\frac{\rho_l-\rho_v}{\rho_v}} \qquad u_n = K_5 u_{n,fl}$$

   - Initially fix K_2= 1 and K_5=0.8
4. Calculate net area $A_n= V_v/u_n$

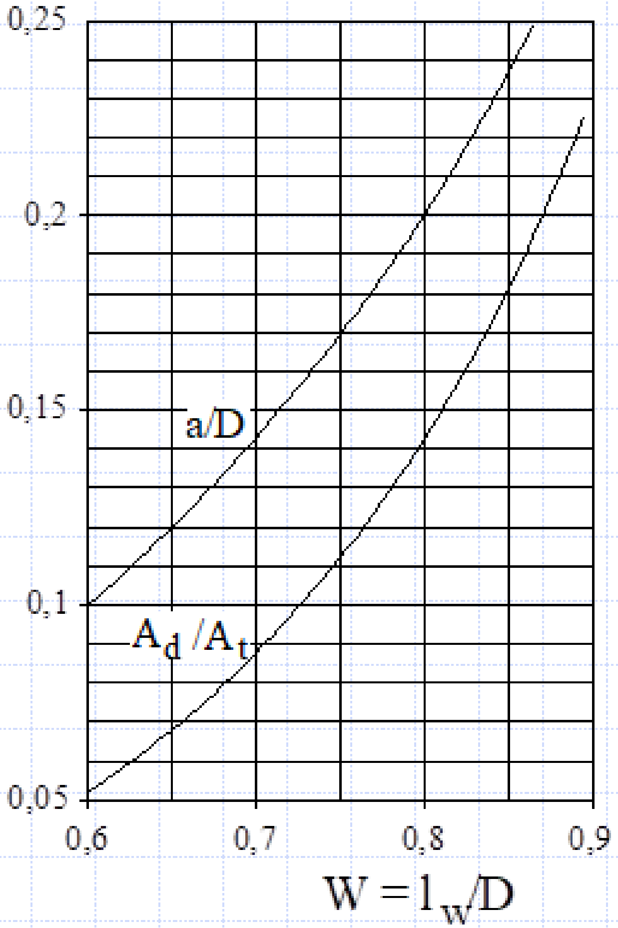
Design of a perforated tray column

5. Calculated total area $A_t = A_n + A_d$



- Downcomer area depends on length l_w
- Fix l_w/D, and the plot gives the A_d/A_t value

$$A_t = \frac{A_n}{1 - A_d / A_t}$$

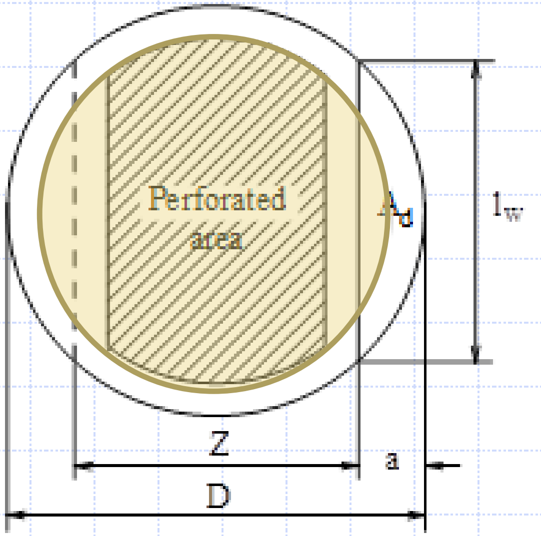


6. Finally diameter is calculated $D = \sqrt{4A_t/\pi}$ and a value for D is chosen closer to the calculated one (> calculated D).

Design of a perforated tray column

K$_2$, K$_5$ and H must be verified

7. K$_2$ verification $K_2=f(A_h/A_a)$



- $A_a = A_t - 2A_d$ OK
- A_h depends on openings geometry. For simple equilateral triangular pass an empirical formula exists:

$$A_h = A_f\, 0.905 \left(\frac{d_h}{p}\right)^2$$

during sizing a value of (d_h/p) must be fixed.

- Area A_f is the active area of a circle:
  $A'_a=A'_t - 2A'_d$ where $A'_t = pD'2/4$ and $D'=D-2b$
  (the value of b must be defined)
  The value of A'_a is obtained from the plot (previous slide) since a=a' and knowing the value of a'/D' → one gets A'_d / A'_t.

Design of a perforated tray column

8. K_5 verification
   - Recalculate $u_{n,fl}$
   - Recalculate u_n
   - Recalculate $K_5 = u_n/u_{n,fl}$
9. Verification that $H > 2h_d$
   1. Fix 2 geometrical parameters: l_{pd} and s

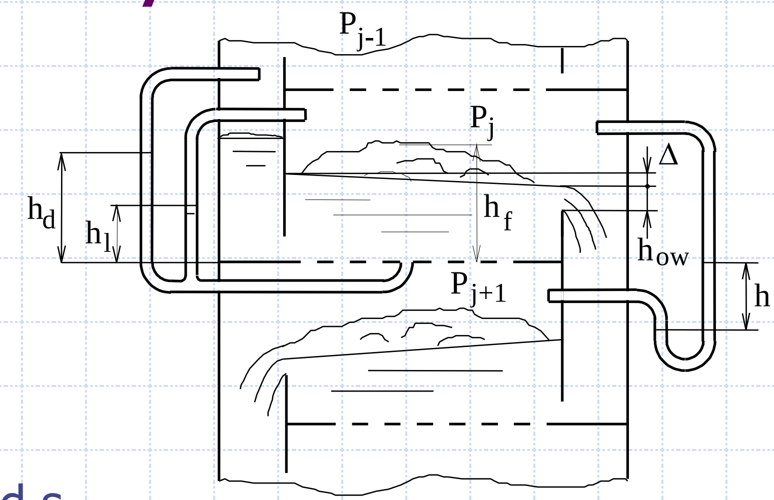
$$h_d = h_t + h_l + h_{pd}$$

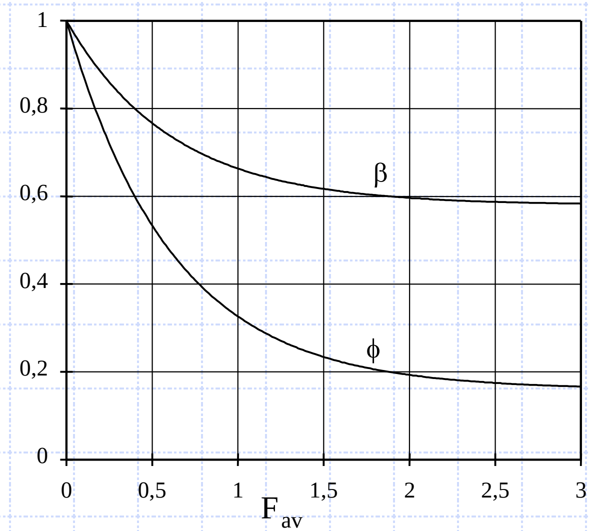
$$h_l = (h_w + h_{ow})\beta$$

$$h_{ow} = 0.67\left(\frac{L_v}{l_w}\right)^{2/3}$$

$$\beta = (1+\phi)/2$$

$$F_{av} = u_a \rho_v^{1/2}$$

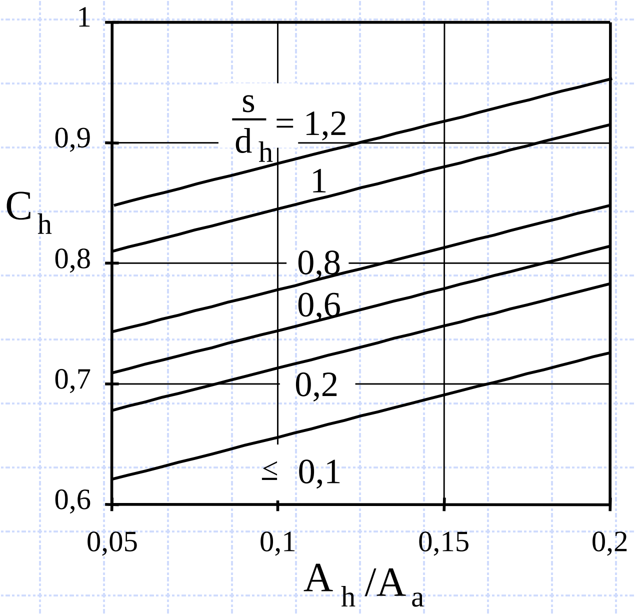




Design of a perforated tray column

- $h_t = h_l + h_h + h_\sigma$
- Pressure drops through openings:

$$h_h = \frac{1}{2g}\frac{\rho_v}{\rho_l}\left(\frac{u_h}{C_h}\right)^2$$



- Note the restriction factor Ch, that depends on the ratio between tray thickness and openings diameter
- Pressure drops due to bubble formation are calculated by a balance of forces (pressure and surface tension) around a bubble of diameter d_b:

$$\pi\frac{d_b^2}{4}P_{ext} + \pi d_b \sigma = \pi\frac{d_b^2}{4}P_{int} \Longrightarrow$$

$$h_\sigma = \frac{4\sigma}{g\rho_l d_h}$$

$$h_{pd} = \frac{1}{2gC_h^2}\left(\frac{L_v}{l_{pd} l_w}\right)^2$$

Diameter estimation: simplified method

- Estimate F_{lv} $$F_{lv} = \frac{L_v}{V_v}\sqrt{\frac{\rho_l}{\rho_v}}$$
- Use Fair correlation to estimate $K_{n,fl}$
- Estimate u_{fl} from $$u_{fl} = K_{n,fl}K_1\sqrt{\frac{\rho_l - \rho_v}{\rho_v}} \qquad K_1 = \left({}^{\sigma}/_{20}\right)^{0.2}$$
- Estimate u as 0.75 * u_{fl}
- Estimate A_{net} from $u = (V\overline{MW_V})/(\rho_V A_{net}(3600))$ in ft/s
- Estimate D from $A_{net} = \eta\, \pi D^2/4$
  - where η is the fraction of the column cross sectional area available for vapor: η = 0.85 – 0.95

Example: D calculation (simple method)

- A sieve-plate distillation column is separating a feed that is 50 mole % n-hexane and 50 mole % nheptane. Feed is a saturated liquid. Plate spacing is 24 in. Average column pressure is 1 atm. Distillate composition is xD = 0.999 (mole fraction n-hexane) and xB = 0.001. Feed rate is 1000 lbmol/h. Internal reflux ratio L/V = 0.8. The column has a total reboiler and a total condenser. Estimate the required diameterat the top of the column.
- Equilibrium data:

x_{C6}	0	0.341	0.398	0.50	1.0
y_{C6}	0	0.545	0.609	0.70	1.0
T, °C	98.4	85	83.7	80	69

Example: D calculation (simple method)

- Solution
  - Since the distillate is almost pure n-hexane, we can approximate properties as pure n-hexane at 69°C.
  - Physical properties (Perry). T = 69°C = 342 K; liquid sp grav. = 0.659 (at 20°); viscosity = 0.22 cP; MW = 86.17.

$$\rho_v = \frac{p(MW)}{RT} = \frac{(1\,\mathrm{atm})(86.17\,\frac{\mathrm{lb}}{\mathrm{lbmol}})}{(1.314\,\frac{\mathrm{atm\ ft^3}}{\mathrm{K\ lbmol}})(342\ \mathrm{K})} = 0.1917\ \mathrm{lb/ft^3}$$

  - ρ_L = (0.659)(62.4) = 41.12 lb/ft^3 (will vary, but not a lot)
  - Surface tension σ = 13.2 dynes/cm
  - $W_L/W_V = L/V\ MW_L/MW_V = L/V = 0.8$
  - Flow parameter $$F_{lv} = \frac{W_L}{W_v}\left(\frac{\rho_v}{\rho_L}\right)^{0.5} = 0.0546$$
  - Ordinate from Fair graph for 24 inch tray spacing, $C_{sb} = 0.36$
  - Then

$$K = C_{sb}\left(\frac{\sigma}{20}\right)^{0.2} = 0.36\left(\frac{13.2}{20}\right)^{0.2} = 0.331$$

Example: D calculation (simple method)

- Solution
  - Flooding velocity: $u_{flood} = K\sqrt{\frac{\rho_L - \rho_v}{\rho_v}} = (0.331)(\frac{41.12 - 0.1917}{0.1917})^{0.5} = 4.836$
  - We will estimate η as 0.90. The vapor flow rate V = L + D. From external mass balances, D = 500.
  - Since L = V * (L/V) → V = D / (1-L/V) = 2500 lbmol/h
  - The diameter D is:

$$\text{Dia} = \sqrt{\frac{4\,V(\overline{MW}_v)}{\pi\,\eta\,\rho_v(\text{fraction})u_{flood}(3600)}}, \qquad \text{ft}$$

  - If perfect gas low holds $\rho_V = P\,MW_V / RT$

$$\text{Dia} = \sqrt{\frac{4VRT}{\pi\,\eta(3600)p(\text{fraction})u_{flood}}}, \qquad \text{ft}$$

$$\text{Dia} = \left[\frac{4(2500)(1.314)(342)}{\pi(0.90)(3600)(1)(0.75)(4.836)}\right]^{1/2} = 11.03\ \text{ft}$$

Rating of a perforated tray column

If the column is available → rating

1. Fair flooding velocity is calculated:

$$K_{n,fl} = f(F_{lv}, H) \qquad u_{n,fl} = K_{n,fl} K_1 K_2 K_3 K_4 \sqrt{\frac{\rho_l - \rho_v}{\rho_v}}$$

2. Net velocity is calculated:

$$u_n = \frac{V_v}{A_n}$$

3. K_5 is calculated

$$K_5 = \frac{u_n}{u_{n,fl}}$$

- If the value is too high, reduce V_v (i.e. feed flow rate F)

General criteria for design

l_w/D: typical value is 0.7
Lower values → dead zones on the tray
Higher values reduces the zone for vapor passage

d_h: $10 < d_h < 25$ mm for systems that create deposits (e.g. polymers)
$5 < d_h < 12$ mm for normal systems

$p/\,d_h$: > 2.5; below 2, vapor flux is unstable and weeping is possible

h_w: typical values are between 15 and 50 mm.
the value chosen is based on pressure to minimize pressure drops

P, bar	h_t, cm H_20	h_w, mm
0,05	< 4	> 13
1	$5 \vert 8$	> 20
20	~ 10	> 25

l_{pd}: normally about 1/2 h_w. Typical values 10 - 25 mm

s: depends on material:
Carbon steel = 4 mm, stainless steel = 3 mm, other materials = 2 mm

Column (Tray) Diameter

- The **minimum column diameter** is typically 0.75 m; otherwise, packed columns are used.
- The **maximum diameter** of the column can be quite large – up to 5 m – although it may be decided to operate 2 or more separate columns in place of an otherwise large diameter single column.
- As the column diameter decreases, the vapor velocity increases for a given vapor flow rate.
  - The minimum column diameter is based upon the maximum vapor velocity that causes excessive entrainment and **flooding**.
  - The maximum column diameter is based upon maintaining a high enough velocity to prevent excess **weeping**.
- The operating vapor velocity, and hence actual column diameter, is specified as a **fraction of the flooding** vapor velocity – typically 0.65 to 0.90.
- The final consideration is **column cost** – a larger diameter column is more expensive than a smaller diameter column, although economies of scale enter into the cost.

Other Factors…

- The total area of the tray hole openings:
  - Typically range from 2 mm to 12 mm
  - Based upon vapor flow per tray
  - Sized to prevent weeping, minimize pressure drop, and reduce entrainment at a given vapor velocity.
- The layout of the tray holes:
  - Different patterns available
  - Layout chosen to ensure an even and well mixed flow of vapor and liquid across the tray so that there are no “dry” spots and bypassing of vapor on the tray that would reduce efficiency.
- The liquid depth on the trays, hence, the weir height:
  - Typically range from 12 to 75 cm
  - Based upon vapor and liquid flow per tray
  - Sized to prevent dry spots, increase liquid-vapor contact time, and to prevent a spray regime that reduces efficiency.

And More Factors…

- The total area and height of the downcomer openings per tray:
  - Based on the passes and the liquid residence time in the downcomer, typically 3 to 7 seconds to allow disengagement of the vapor from the liquid in the downcomer to prevent flooding.
  - The downcomer height should be at least ½ the height of the tray spacing.
  - Additional passes are chosen to prevent excessive loading of the downcomers.
- The tray spacing:
  - Typically 0.15 to 1 m in small diameter columns (< 6m) with larger spacing in large diameter columns to allow maintenance access.
  - Based upon the liquid disengagment zone required between the trays to avoid entrainment and flooding.
  - The tray spacing and number of trays, plus the inlet and outlet sections, determine the overall column height.

And Even More Factors…

- The tendency of the liquid-vapor mixture to foam or a “foaming factor” that affects the tray spacing for disengagement and downcomer height, as well as the efficiency.
- The type of tray – sieve, bubble cap, or tray – which will affect the pressure drop, entrainment, flooding, weeping, and efficiency characteristics, as well as the cost, of the column.

Tray Comparison

- The turndown ratio is the ratio of the maximum vapor flow rate (flooding) to minimum vapor flow rate (excessive weeping).

Table 6.2 Comparison of Types of Trays

	Sieve Trays	Valve Trays	Bubble-Cap Trays
Relative cost	1.0	1.2	2.0
Pressure drop	Lowest	Intermediate	Highest
Efficiency	Lowest	Highest	Highest
Vapor capacity	Highest	Highest	Lowest
Typical Turndown ratio	2	4	5

Column Diameter – Some Final Notes

- Since each stage is at a different operating temperature and the actual vapor flow rate may change substantially throughout the column if CMO is not applicable, the flooding velocity, operating velocity, and required diameter of the column change at each stage.
- One usually calculates all of the column diameters at each stage, and uses the largest diameter for the design.
- One can also design a column that has different diameters at different sections of the column if it is cost effective to do so, or if too large of a column diameter may lead to excessive weeping in a given section of the column.
- Once one obtains the column diameter(s), they are usually rounded up to the next 0.5 ft or 0.1 m increment since manufacturers typically deliver trays and shells at these increments.