Module # 7

PROCESS DESIGN OF MASS TRANSFER COLUMN: DESIGN OF DISTILLATION AND ABSORPTION COLUMN

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Lecture 1: Introduction

1. Introduction

The typical gas-liquid contacting operations include distillation, absorption, stripping, leaching and humidification. Distillation and absorption are two most widely used mass transfer processes in chemical industries. Design of plate column for absorption and distillation involves many common steps of calculation such as determination of number of theoretical plates, column diameter, plate hydraulic design, etc.In absorption process, a soluble component is absorbed in a liquid (called solvent) from a gaseous mixture. The gas and liquid streams leaving the tray are in equilibrium under the ideal condition. The separation in distillation is based on the relative volatility of the components. Additional vapor phase is generated by the vaporization of more volatile components (called stripping) and by condensation of relatively less volatile components(called absorption) adds to the liquid phase.

Selection of column type: Plate or Packed: Packed towers (columns) are also used as the contacting devices for gas absorption, liquid-liquid extraction and distillation. The gaseous mixture is allowed to contact continuously with the liquid counter-currently in a packed column. The liquid flows downward over the packing surface, and the gaseous mixture flows upward through the space in the packing. The performance of the column strongly depends on the arrangement of the packings to provide good liquid and gas contact throughout the packed bed. The solute gas is absorbed by the fresh solvent (liquid) entering at the top of the tower where the lean gas leaves system. The liquid enriched with absorbed solute gas, leaves the column bottom through the exit port.

In a plate tower, the liquid and gas are contacted in stage-wise manner on the trays; while gas-liquid contact is continuous in a packed column. There are always some uncertainly to maintain good liquid distribution in a packed tower. For this reason, it is difficult to accurately estimate the packed tower efficiency. The course content is limited to design of plate column only and some typical criterions for the selection of column type are discussed below.

- Plate towers exhibit larger pressure drops and liquid holdup at higher gas flow rate. While, packed towers are not appropriate for very low liquid flow rates. Packed column is the preferred choice than a plate column to handle toxic and flammable liquids due to lower liquid holdup to keep the unit as small as possible for the sake of safety.
- Plate columns are normally suitable for fouling liquids or laden with solids. They are easier to clean and could handle substantial temperature variation during operation.
- Packed towers are more suitable for foaming and corrosive services.
- It is easier to make the provision for the installation of internal cooling coils or withdrawal of side streams from a plate column.

2. Plate contractors

Plate contractors/ towers are vertical cylindrical columns in which a vertical stack of trays or plates are installed across the column height as shown in Figure 7.1. The liquid enters at the top of the column and flows across the tray and then through a downcomer (cross-flow mode) to the next tray below. The gas/vapor from the lower tray flows in the upward direction through the opening/holes in the tray to form a gas-liquid dispersion. In this way, the mass transfer between the phases (gas/vapor-liquid) takes place across the tray and through the column in a stage-wise manner.

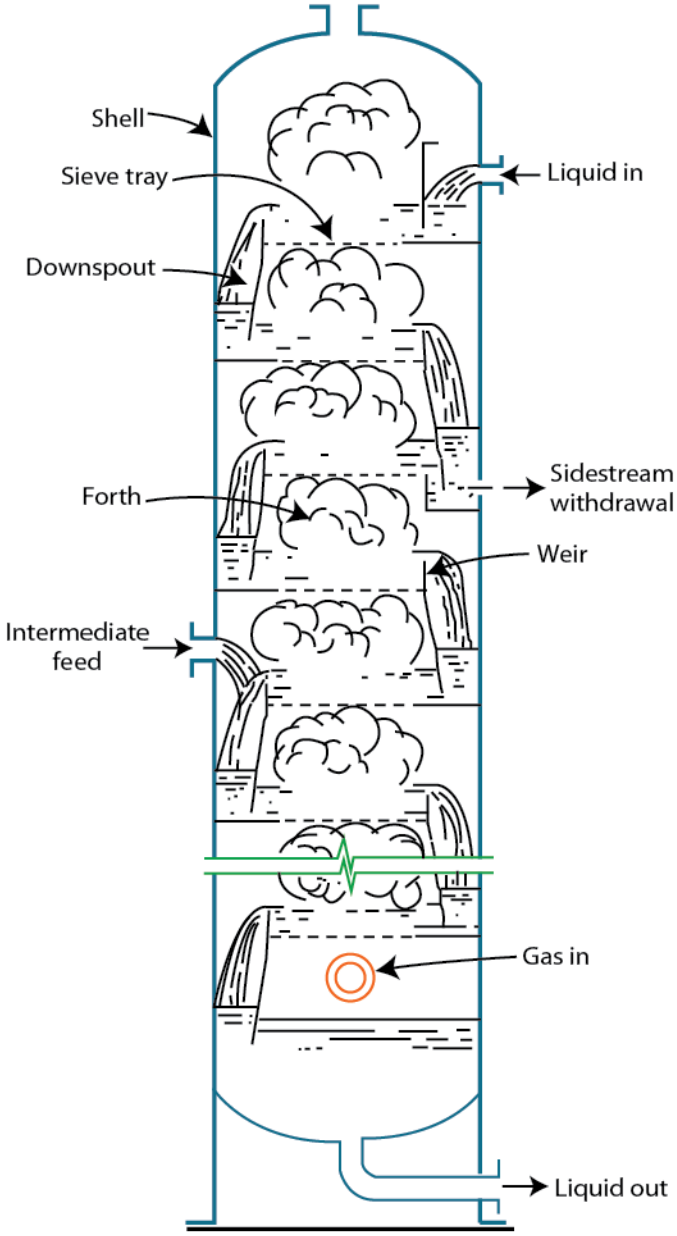

Figure 7.1. Schematic diagram of a plate contractor ([1] page 159).

7.1. Definition of tray areas

The definition of tray areas and its nomenclature illustrated in Figures 7.2 &7.3 are followed throughout the design procedure.

Total tower cross-section area (A_T): The empty tower inside cross-sectional area without trays or downspouts.

Net area (A_N) (also called free area): The total tower crosssectional area (A_T)minus the area at the top of the downcomer (A_{DT}). The net area symbolizes the smallest area available for vapor flow in the inter-tray spacing.

Bubbling area or active area (A_A): The total tower cross-sectional area minus sum of the downcomer top area(A_{DT}) and downcomer seal area (A_{DB})and any other nonperforated areas on the tray. The bubbling area represents the area available for vapor flow just above the tray floor.

Hole area (A_h): The total area of the perforations on the tray. The hole area is the smallest area available for vapor/gas passage.

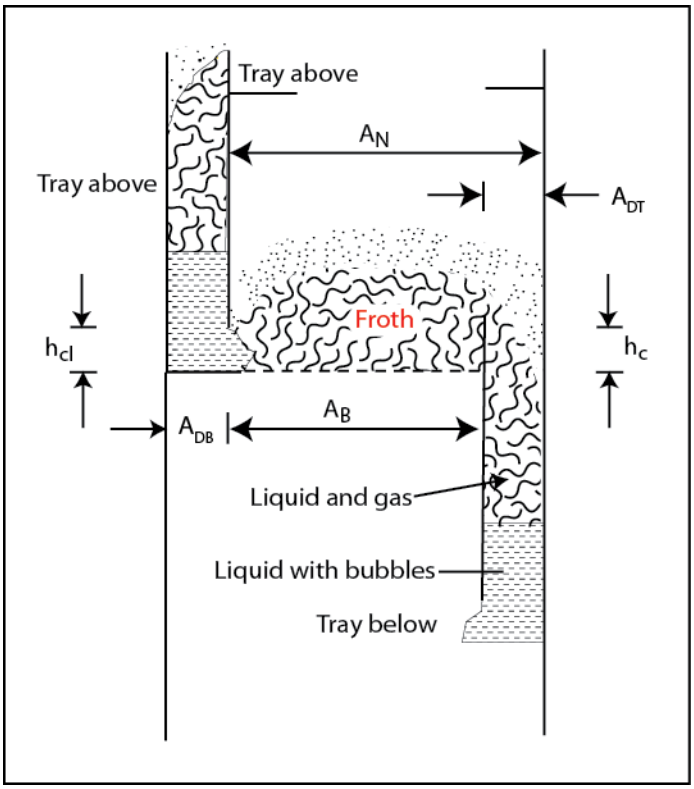

Figure 7.2.Schematic of a tray operating in the froth regime ([2] page 14-28).

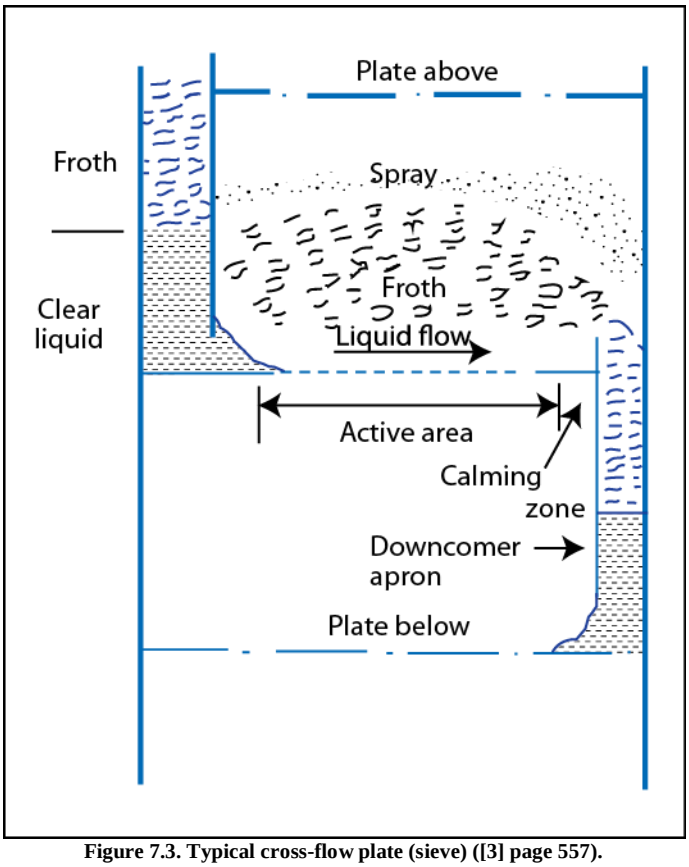

Figure 7.3. Typical cross-flow plate (sieve) ([3] page 557).

7.2. Plate types

Gas and liquid flow across the tray can either be by cross-flow or counter-flow manner (Figure 7.4). The cross-flow plates are most widely practiced and the three main types of cross flow plates are: bubble cap, valve and sieve trays with downcomer.

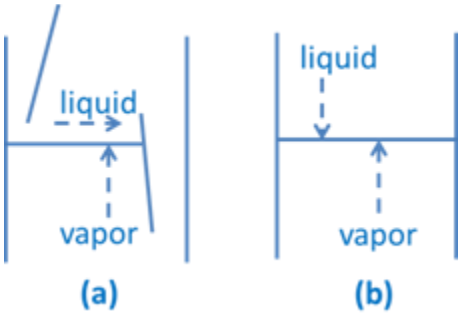

Figure 7.4. Classification of plate types based on flow mode- side view shown: (a) Cross-flow plate, (b): Counterflow plate.

7.2.1. Bubble cap plates

An enhanced gas-liquid contact can be achieved having bubble caps on the tray at very low liquid flow rates. A bubble cap consists of a riser (also called chimney) fixed to the tray through a hole and a cap is mounted over the riser (Figure 7.5). The gas flows up through the riser, directed downward by the cap through the annular space between riser and cap. Finally, the gas is dispersed into the liquid. A number of slots in the lower part of the cap help in gas bubble dispersion. Un-slotted types of cap designs are also common in application. Bubble caps are especially suitable for higher turndown ratio. Turndown ratio is the ratio of maximum operating vapor rate to the minimum allowable vapor rate, below which weeping starts.

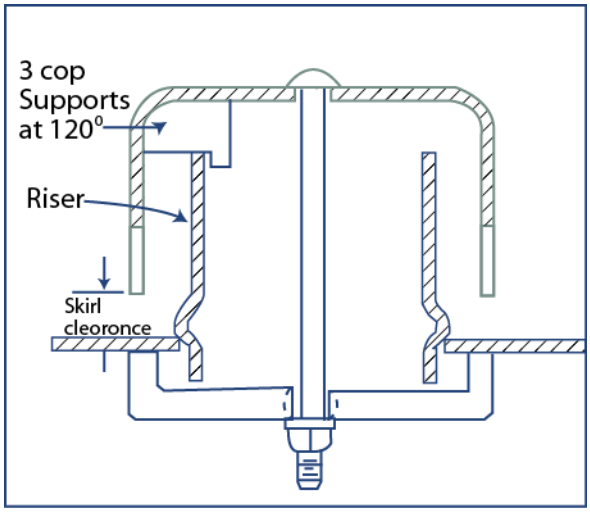

Figure 7.5. Bubble caps ([1] page 166).

7.2.2. Valve plates

Valve trays (or floating cap plate) are the modified design of sieve trays where relatively large plate perforations are covered by movable caps/valves (Figure 7.6). Valves cover may be round or rectangular. The very common hole diameter is 40 mm but upto 150 mm are also used. The valve lifts up as the vapor flow rate increases and the valve sits over the perforation at lower flow rate, thus stops the liquid from weeping. Valve trays provide good vapor-liquid contact at low flow rates (high turndown ratio).

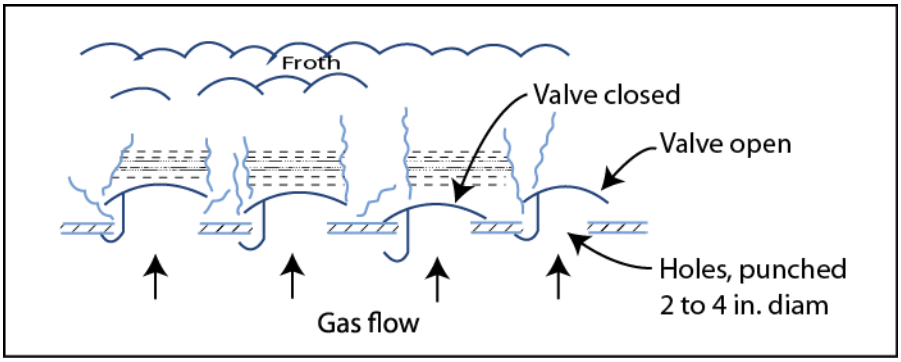

Figure 7.6. Valve tray ([4] page 14-25).

7.2.3. Sieve plate

The sieve tray (also known as perforated plate) is a flat perforated metal sheet (Figure 7.7). The hole diameter from 1.5 to 25 mm are very commonly used. The sieve tray layout is a typical square or equilateral triangular pitch holes. The gas/vapor flows upward through the perforation and disperses into the flowing liquid over the plate. There is no liquid seal in case of trays without downcomer and the liquid weeps (called weeping) through the holes at low flow rates, reducing the efficiency of plate. For this reason, sieve tray has the lowest turndown ratio. Sieve tray construction is simple and relatively cheap.

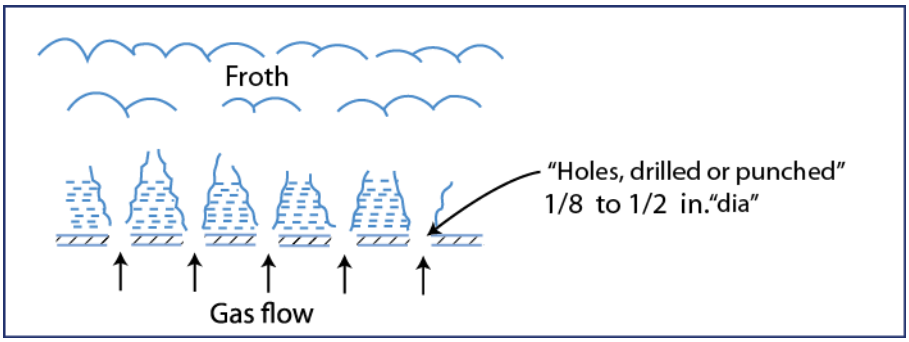

Figure 7.7. Sieve tray ([4] page 14-25).

7.2.4. Selection of tray type

The comparative performances of three common types of trays are summarized in Table 7.1.

The capacity, efficiency, pressure drop and entrainment of sieve and valve trays are almost same.

Bubble cap trays have lower capacity and efficiency and but higher pressure drop and entrainment compared to valve and sieve trays. The turndown ratio comes in the order of: bubble cap>valve>sieve. However, valve trays have the best turndown ratio in case of refinery applications. Sieve trays are the least expensive and suitable for almost all applications. Valve trays can be considered where higher turndown ratio is needed. Bubble cap trays should be used at very low liquid flow rate which is not achievable using sieve trays.

Table 7.1: Comparison of three types of cross-flow trays ([5] page 266).

Tray type	Capacity	Efficiency	Pressure drop	Entrainment	Turndown ratio	Cost
Bubble cap	Medium high	Medium high	High	~3 times than sieve tray	Excellent	100-200 % more than sieve tray
Valve	High to very high	High	Medium to high	Medium	4 to 10.1	20-50% more than sieve tray
Sieve	High	High	Medium	Medium	2.1	Cheapest of all types

Lecture 2: Effect of Vapor Flow Conditions on Tray Design

7.3. Effect of vapor flow conditions on tray design

7.3.1. Flooding consideration

Excessive liquid buildup inside the column leads to column flooding condition. The nature of flooding depends on the column operating pressure and the liquid to vapor flow ratio. It may be downcomer backup, spray entrainment or froth entrainment type floodings.Higher tray pressure drop due to excessive vapor flow rates holds up the liquid in the downcomer, increases the liquid level on the plate and leads to downcomer flooding situation. The column flooding conditions sets the upper limit of vapor velocity for steady operation.

Gas velocity through the net area at flooding conditioncan be estimated using Fair's correlation (**[4], page 14-26**):

$$U_{nf} = C_{sbf}\left(\frac{\sigma}{20}\right)^{0.2}\left(\frac{\rho_l-\rho_v}{\rho_v}\right)^{0.5} \quad \text{[m/s]} \qquad (7.1)$$

ρ_v = vapor density, kg/m^3
ρ_l = liquid density, kg/m^3
σ = liquid surface tension, mN/m (dyn/cm)

C_{sbf} = capacity parameter (m/s) can be calculated(**[4] page 14-27**) in terms of plate spacing and flow parameter $F_{LG} = \frac{L}{V}\left(\frac{\rho_v}{\rho_l}\right)^{0.5}$ (7.2)

L =liquid flow rate, kg/s

V =vpor flow rate, kg/s

The design gas velocities (U_n) is generally 80-85% of U_{nf} for non-foaming liquids and 75% or less for foaming liquids subject to acceptable entrainment and plate pressure drop.

7.3.2. Sieve tray weeping

Weeping occurs at low vapor/gas flow rates. The upward vapor flow through the plate perforationsprevents the liquid from leaking through the tray perforation. At low vapor flow rates, liquid start to leak/rain through the perforation (called weeping). When none of the liquid reaches the downcomer at extreme weeping condition at very low vapor flow rate, it is called dumping. The weeping tendency increases with increasing fractional hole area and liquid flow rates.

The vapor velocity at the weep point (where liquid leakage through holes starts) is the minimum value for stable operation. For a chosen hole area,the minimum operating vapor flow velocity ($U_{min\,,op}$) at minimum flow rate for stable operation should be above weep point vapor velocity.

The minimum vapor velocity ($U_{\min}$) at the weep point (**[3] page 569**):

$$U_{\min} = \frac{K_2 - 0.9(25.4 - d_h)}{{\rho_v}^{1/2}} \qquad (7.3)$$

Where, d_h = hole diameter, mm,

ρ_v = vapor density, kg/m^3 (maximum value of vapor density)

K_2 = constant (K_2) of weep-point correlation depends on the depth of clear liquid (weir crest + weir height) on the plate (**[3] page 571**).

Weir crest (h_{wc}) can be determined using the Francis' weir correlation (**[3] page 571**):

$$h_{wc} = 750\left(\frac{L_{wc}}{L_W \rho_l}\right)^{2/3} \quad [\text{mm}] \qquad (7.4)$$

L_{WC}=weir length, m

L_W=liquid flow rate over the crest, kg/s

ρ_l = liquid density, kg/m^3

Actual operating minimum vapor velocity: $U_{min\,,op} = \frac{\text{minimum vapor flow rate}}{\text{hole area}}$ [m/s] (7.5)

To avoid weeping: $U_{min\,,op} > U_{\min}$.

7.3.3. Liquid entrainment

Entrainment is the phenomena in which liquid droplets are carried by vapor/gas to the tray above. Therefore, the less volatile liquid components from bottom tray are mixed with liquid having relatively more volatile materials on the overhead tray. It counteracts the desired mass transfer operation and the plate efficiency decreases. Entrainment increases with vapor velocity.The fractional entrainment ($\Psi = \frac{\text{kg}}{\text{kg gross liquid flow}}$) can predicted using Fair's correlation in terms of the flow parameter [$F_{LG} = \frac{L}{V}\left(\frac{\rho_v}{\rho_l}\right)^{0.5}$] and actual flooding velocity (**[4] page 14-28**).

Effect of Ψ on Murphree plate efficiency can be estimated using Colburn equation (**[4] page 14-29**):

$$E_a = \frac{E_{mv}}{1+\frac{\Psi E_{mv}}{1-\Psi}} \quad (7.6)$$

E_{mv} =Murphree vapor efficiency

E_a=Corrected Murphree vapor efficiency for liquid entrainment

7.4. Tray hydraulic parameters

Total plate pressure drop

All gas pressure drops (h_t) are expressed as heads of the clear liquid and $h_t$is given by:

$$h_t = h_d + (h_{wc} + h_w) + h_r \quad (7.7)$$

Where, h_d =dry plate pressure drop, mm

h_{wc} =height of liquid over weir (weir crest), mm

h_w =weir height, mm

h_r=residual head, mm

Dry plate pressure drop (h_d):

Dry plate pressure drop occurs due to friction within dry short holes.$h_d$can be calculated using following expression derivedfor flow through orifices (**[3] page 575**).

$$h_d = 51\left(\frac{U_{max}}{C_0}\right)^2 \frac{\rho_v}{\rho_l} \quad \text{[mm]} \quad (7.8)$$

Maximum vapor velocity: $U_{max} = \frac{\text{Maximum volumetric vapor flow rate}}{A_H}$

(7.9)

The orifice coefficient, C_0 can be determined in terms of $\frac{A_H}{A_P}$and $\frac{\text{plate thickness}}{\text{hole diameter}}$**([3] page 576)**.

Residual gas pressure head (h_r):

The residual pressure drop results mainly from the surface tension as the gas releases from a perforation. The following simple equation can be used to estimate $h_r$with reasonable accuracy (**[3] page 575**).

$h_r = \frac{12.5\times10^3}{\rho_l}$

(9.10)

Downcomer backup (h_b) and downcomer residence time:

The liquid level and froth in the downcomer should be well below the top of the outlet weir on the tray above to avoid flooding (**[3] page 576**).

$h_b = (h_{wc} + h_w) + h_t + h_{dc}$

(7.11)

Head loss in downcomer: $h_{dc} = 166\left(\frac{L_{wd}}{\rho_l A_m}\right)^2$

(7.12)

L_{wd} = Downcomer liquid flow rate, kg/s

A_m =Smaller of clearance area under the downcomer apron (A_{ap}) and downcomer area(A_D)

The average density of aerated liquid in the dowmncomer can be assumed as $\frac{1}{2}$ of the clear liquid density.Therefore, half of the sum of the plate spacing and weir height should be greater than thedowncomer backup.

$$\frac{1}{2}(\textbf{plate spacing} + \textbf{weir height}) > h_d \qquad (7.13)$$

Downcomer residence time (t_{drt}) should be sufficient for the disengagement of liquid and vapor in the downcomer to minimize entrained vapor. The value of t_{drt} >3 s is suggested. Downcomer residence timeis given by (**[3] page 578**):

$t_{drt} = \frac{A_D h_{bc} \rho_l}{L_{wd}}$ [s]

(7.14)

h_{bc} = clear liquid back up, mm

Lecture 3: Plate Design

7.5. Column sizing approximation

The column sizing is a trial anderror calculationprocedure,starting with a tentative tray layout. The calculation is then revised until anacceptable design is obtained subject to satisfyingthetray pressure drop, weeping, flooding and liquid entrainment limits. The column sizing is carried at the tray where the anticipated column loading is the highest and lowest for each section. However, the vapor flow rates have the highest impact on tower diameter. For an example, the sizing calculation is performed on the top tray for the above feed section and on the bottom tray for below feed section, for a single feed distillation column with one top and one bottom product. The tray spacing determines the column height. Lower tray spacing is desirable to minimize construction cost by checking against the column performance criteria. The suggested tray spacing (T_t) with column diameter is appended below (**[1] page 162**). The detailed column sizing calculations are discussed in the solved example.

Tower diameter, m	Tray spacing, mm
1 or less	500 (150 mm is minimum)
1-3	600
3-4	750
4-8	900

7.6. Provisional plate design

7.6.1. Column diameter

The column diameter is determined from the flooding correlation for a chosen plate spacing. The superficial vapor/gas velocity (U_{nf}) at flooding through the net area relates to liquid and vapor densities according to Fair's correlation (**refer to section7.3.1**).C_{sbf} is an empirical constant, depends on tray spacing and can be estimated against the flow parameter (F_{LG}) based on mass flow rate of liquid (L) and vapor (V) (**[3] page 567, [4] page 14-27**).

Typically, the design velocity (U_n) through the net area is about 80 to 85% of U_{nf} for non-foaming liquids and 75% or less for foaming liquid depending on allowable plate pressure drop and entrainment. It is a common practice to have uniform tower diameter in all sections of the column even though the vapor/gas and liquid loadings are expected to

be different to minimize the cost of construction. The uniformity in tower diametermay require selecting different plate spacing in different sections of the tower.

7.6.2. Hole diameter,hole pitchand plate thickness

The plate hole diameters (d_h) from 3 to 12 mm are commonly used. The bigger sizes are susceptible to weeping. The holes may be drilled or punched and the plate is fabricated from stainless steel and other alloys than carbon steel. The centre to centre distance between two adjacent holes is called hole pitch (I_P). Perforations can be arranged in square or equilateral triangular arrays with respect to the vapor/gas flow direction. The normal range of I_P is from 2.5 to 5 times of d_h (**[1] page 168**).

For triangular pitch: $\frac{A_H}{A_P} = 0.907\left(\frac{d_h}{I_P}\right)^2$

(7.15)

Plate thickness (t_t) typically varies from 0.2 to 1.2 times of the hole diameter and should be verified by checking the allowable plate pressure drop (**[3] page 576**).

7.6.3. Weir heightand weir length

The depth of liquid on the tray is maintained by installing a vertical flat plate, called weir. Higher weir height (h_w) increases the plate efficiency. But it increases plate pressure drop, entrainment rate and weeping tendency. Weir heights from 40 to 90 mm are common in applications for the columns operating above the atmospheric pressure. For vacuum operation, h_w=6 to 12 mm are recommended. The weir length (L_w) determines the downcomer area. A weir length of 60 to 80% of tower diameter is normally used with segmental downcomers. The dependency of L_w on downcomer area is calculated against the percentage value of $\frac{A_D}{A_A}$ (**[3] page 572**).

7.6.4. Calming zones

Two blank areas called calming zone, are provided between the inlet downcomer or inlet weir and the perforation area, and also between the outlet weir and perforation area. Inlet calming zone helps in reducing excessive weeping in this area because of high vertical velocity of the entering liquid in the downward direction. Outlet calming zone allows disengagement of vapor before the liquid enters the downcomer area. A calming zone between 50 to 100mm is suggested.

3. Stepwise design tray procedure

Iterative tray design approach (**[3] page 566**) is listed below. The design is performed separately both above feed plate (top section) and below feed plate (bottom section) for single feed two product distillation column.

Step #1: Determine the number of theoretical plate and vapor and liquid flow-rates separately both in top and bottom sections.
Step #2: Obtain the physical properties of the system
Step #3: Select a trial plate spacing
Step #4: Estimate the column diameter based on flooding considerations
Step #5: Decide the liquid flow arrangement (reverse, single-pass, or multiple-pass). A guideline is provided in Figure 11.28 (**[3] page 568**).
Step #6: Make a provisional tray layout including downcomer area, active area, perforated area, hole area and size, weir height, weir length
Step #7: Check the weeping rate, if not satisfactory go back to step #6 and reselect tray layout
Step #8: Check the plate pressure drop, if too high return to step #6
Step #9: Check downcomer back-up, if too high go back to step #6 or #3
Step #10: Decide plate layout including calming zones and unperforated areas and check hole pitch, if unsatisfactory return to step #6
Step #11: Recalculate the percentage of flooding based upon selected tower diameter
Step #12: Check for entrainment, if too high then return to step #4
Step #13: Optimize design: repeat steps #3 to #9 to find smallest diameter and plate spacing acceptable to get the lowest cost for the specified application
Step #14: Finalize design: draw up the plate specification and sketch the layout

Lecture 4: Hand on Design

4. Design problem

Design a continuous distillation column (plate) to recover acetone from a 50-50 mole % acetone-water mixture available at 30°C. The feed stream flow rate is 25,000 kg/h. The top product should contain at least 95 mole% acetone and the bottom product should contain <1 % acetone by mole. Consider reboiler as equivalent to one stage. This column is operated at atmospheric pressure (top tray). Column efficiency of 60% and pressure drop per plate of 1.25 kPa may be assumed. You can take the minimum liquid flow as 70% of the maximum rate both above and below the feed plate. The vapor liquid equilibrium (VLE) data for the acetone-water system at atmospheric pressure is provided in Table 7.2.

Data given:

Latent heat of water= 41,360 J/mol; latent heat of acetone= 28,410 J/mol

Specific heat of water=75.3 J/mol°C (mean); Specific heat of acetone 128 J/mol°C (mean)

Table 7.2: VLE data for the acetone-water system at 1 atm.

x	0.0	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	**0.50**	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95
y	0.0	0.6381	0.7301	0.7716	0.7916	0.8034	0.8124	0.8201	0.8269	0.8376	**0.8387**	0.8455	0.8532	0.8615	0.8712	0.8817	0.895	0.9118	0.9335	0.9627
BP, °C	100	74.8	68.53	65.26	0.63.59	62.6	61.87	61.26	60.75	60.35	**59.95**	59.54	59.12	58.71	58.29	57.9	57.49	57.08	56.68	56.3

x= Mole fraction of acetone in liquid; y= Mole fraction of acetone in vapor; BP: Bubble point

Step #1: Mass balance and determination of number of theoretical stage

Feed and products compositions:

Component	***Feed mole fraction***	***Top product mole fraction***	***Bottom product mole fraction***
Acetone	0.50	0.95	0.01
Water	0.50	0.05	0.99

Bubble point of feed (from the data shown in table) = 59.95°C

Latent heat of the feed = 28,410×0.5 + 41,360×(1 - 0.5) = 34,885 J/mol

Specific heat of the feed = (128×0.5) + 75.3× (1 - 0.5)= 101.75 J/mol °C

Heat required to vaporize 1 mole of the given feed = (59.95 - 30) ×101.75 + 34,885=37933 J

$$q = \frac{\text{Heat required to vaporize 1 mole of the given feed}}{\text{Latent heat of the feed}} = \frac{37933}{34885} = 1.09$$

Slope of the q-line$= \frac{q}{q-1} = \frac{1.09}{1.09-1} = 12.44$

Here, the top operating line just touches the equilibrium curve at the point of tangency of the rectifying section operating line at which the minimum reflux takes place.

From the Figure 7.8: $\frac{x_D}{R_{\min}+1} = 0.57$; R_{min}= 0.67 for x_D=0.95

Here, **reflux ratio**, $\boldsymbol{R}$=2.5×R_{min} =2.5×0.67= 1.675 is taken for this design.

Average molecular wt. of feed= 0.5×58 + 0.5×18=38

Molar feed flow (F) rate=25,000/38=657.9 kmol/h

Acetone balance: $D \times 0.95 = 657.9 \times 0.5 \Rightarrow D = 346.2$ kmol/h

Vapor flow (V) rate above feed plate, $V = D(1 + R) = 346.2(1 + 1.675) =$ 926.2 kmol/h

(Assuming constant molar overflow)

Top section liquid flow rate, $L = V - D = 580$ kmol/h

Bottom product: $B = F - D = 657.9 - 346.2 = 311.7$ kmol/h

Mass balance below feed plate: $L' = V' + B$

Slope of the bottom section operating line (Figure 7.8): $\frac{L'}{V'} = 1.32$

L'= Liquid flow rate below feed plate = 1285.7 kmol/h

V'= Vapor flow rate below feed plate = 974 kmol/h

The construction of operating lines and number of theoretical stages are shown in this Figure 7.8.

Total number of tray= 6 (above feed) +3 (below feed) =**9**

Total number of real stages= $\frac{9-1}{0.6} \approx 14$ (60% column efficiency; reboiler was considered as equivalent to one theoretical tray)

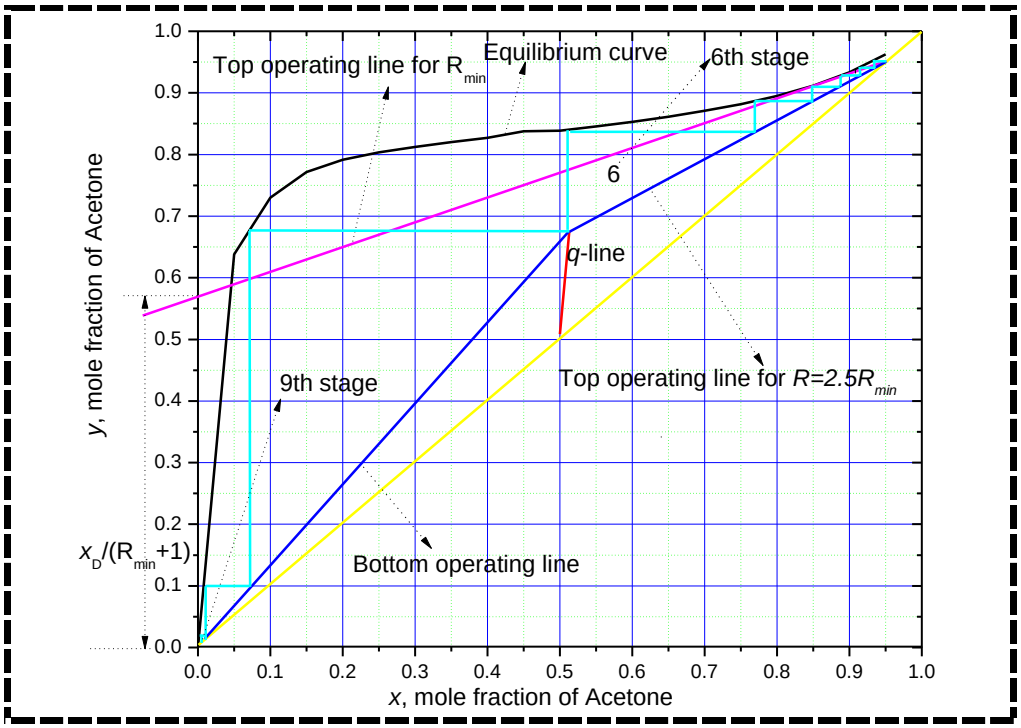

Figure 7.8: McCabe-Thiele construction.

Step #2: Estimation of physical properties

Column top pressure= 101325 Pa (1 atm) Column pressure drop=$1.25\times10^3\times14$=16800 kPa Pressure drop of 1.25kPa per tray is specified	
Top section:	**Bottom section:**
Column top pressure= 101325 Pa (1.0147 bar) and temperature= 56.3 °C $\rho_v = \frac{PM}{RT} = \frac{101325\times56.5}{329.3\times8.314\times10^3} = 2.08$ kg/m^3 ρ_l =744 kg/m^3 (density of the mixture) (water density= 985 and acetone density= 735 kg/m^3 at 56.3 °C) Average molecular weight of vapor: M=56.5 Average molecular weight of liquid: M=56 Surface tension, σ =20×10^{-3} N/m	Column bottom pressure=101325 +16800 = 118825 Pa (=1.19 bar) Boiling point of water at 118825 Pa (1.19 bar)= 105 °C (bottom contains 99 mole % water) From the steam table at 118825 Pa and 105 °C: ρ_v = 0.693; ρ_l = 955 kg/m^3 Average molecular weight of vapor: M=40.58 Average molecular weight of liquid: M=18.4

	$\sigma = 58 \times 10^{-3}$ N/m

Lecture 5: Provisional Plate Design

Step #3: Plate spacing

Plate spacingof 600 mm is considered for the first trial to calculate capacity parameter (C_{sbf}) for the estimation of maximum allowable vapor velocity through the net plate area (**[3] page 567, [4] page 14-27**). The suggested plate spacing is 600 mm for column diameter>1.5 m.

Step #4: Column diameter (refer to sections 7.3.1 &7.6.1; Eqs. 7.1 & 7.2)

1st trial is started with the following considerations:

- Design is performed for 80% flooding at maximum gas flow rate.
- Total downcomer top and bottom seal area is 10% of the net area.

Top section:	**Bottom section:**
Flow parameter (F_{LG}) based on mass flow rate, $\frac{L}{V}\left(\frac{\rho_v}{\rho_l}\right)^{0.5} = \frac{580\times56}{926.2\times56.5}\left(\frac{2.08}{744}\right)^{0.5}$=0.033	F_{LG}=$\frac{L'}{V'}\left(\frac{\rho_v}{\rho_l}\right)^{0.5}$ $= \frac{1285.7\times18.4}{974\times40.58}\left(\frac{0.693}{955}\right)^{0.5}$=0.016
Capacity parameter (C_{sbf}) $= 0.12$ m/s	$C_{sbf} = 0.11$ m/s
Gas velocity through the net area at flooding: $U_{nf} = C_{sbf}\left(\frac{\sigma}{20}\right)^{0.2}\left(\frac{\rho_l-\rho_v}{\rho_v}\right)^{0.5} = 0.12 \times \left(\frac{20}{20}\right)^{0.2}\left(\frac{744-2.08}{2.08}\right)^{0.5} = 2.26$ m/s [σ = liquid surface tension, mN/m]	$U_{nf} = C_{sbf}\left(\frac{\sigma}{20}\right)^{0.2}\left(\frac{\rho_l-\rho_v}{\rho_v}\right)^{0.5}$ $= 0.11 \times \left(\frac{58}{20}\right)^{0.2}\left(\frac{955-0.693}{0.693}\right)^{0.5}$ $= 5.05$ m/s
The linear design gas velocity (U_n) based on net area (80% flooding): $U_n = 0.8 \times 2.26 = 1.8$ m/s	$U_n = 0.8 \times 5.05 = 4.04$ m/s
The maximum volumetric vapor flow rate (Q_{max}): $Q_{max} = \frac{V\times M}{\rho_v} = \frac{926.2\times56.5}{2.08}$ =25158.8 m^3/h=6.98 m^3/s	$Q_{max} = \frac{V\times M}{\rho_v} = \frac{974\times40.58}{0.693}$ = 57034.5 m^3/h=15.84 m^3/s

Net area required: $\frac{Q_{max}}{U_n} = \frac{6.98}{1.8}$ =3.88 m^2	$\frac{Q_{max}}{U_n} = \frac{15.84}{4.04}$ =3.92 m^2
Totals tower cross-section area: $\frac{3.88}{0.9}$ =4.31 m^2 (Total downcomer top and bottom seal area is 10% of the net area)	$= \frac{3.92}{0.9}$ =4.36 m^2
Colum (tower) diameter: $\sqrt{\frac{4.31}{0.785}}$ =2.34 m	Colum (tower) diameter: $\sqrt{\frac{4.36}{0.785}}$ =2.36 m
Use the highervalue of the tower diameter for the uniformity between sections, if the difference is not greater than 20%. In this case, the bottom diameter is used both in top and bottomsections. Higher area than the design area (here top section) can be taken care by reducing the perforated area. **The nearest recommended shell (nominal diameter 2400 mm) fabricated from carbon steel or stainless steel sheet in IS 2844-1964: ID 2403 mm with minimum wall thickness: 8 mm for carbon steel) and 6 mm for stainless steel.**	

Step #5: Selection of liquid-flow arrangement

Liquid volumetric flow rate in the top section $= \frac{580 \times 56}{3600 \times 744} \approx 0.012 m^3/s$

Liquid volumetric flow rate in the top section $= \frac{1285.7 \times 18.4}{3600 \times 955} \approx 0.007 m^3/s$

Therefore, single pass cross-flow sieve plate is chosen for this service (**[3] page 568**).

Step #6: Provisional plate design (refer to sections 7.6.2 & 7.6.3)

Column (tower) diameter (ID): $D_T \approx 2.4$ m

Column cross-section area: $A_T = 0.785 \times {D_T}^2 = 4.52$ m^2

Downcomer area: $A_D = 0.1 A_T = 0.452$ m^2

Net area: $A_N = A_T - A_D = 4.068$ m^2

Weir Length (l_W) = 0.73×D_T = 1.752 m (**[3] page 573**)

Weir height, h_w = 40 mm is considered.

Active area: $A_A = A_T - 2 \times A_D$ =3.616 m^2

For the first trial, consider hole diameter: d_h=12 mm ($\frac{1}{2}$inch). The plate thickness=hole diameter is selected for the first trial.

Step #7: Checking for weepage (refer to section 7.3.2; Eqs. 7.3 & 7.4)

Top section	**Bottom section**
Maximum liquid flow rate (m_{max})= $\frac{580\times56}{3600}$ =9.02 kg/s	m_{max} = $\frac{1285.7\times18.4}{3600}$ =6.571 kg/s
Minimum liquid flow rate (m_{min}) (70% of m_{max})=0.7×9.02=6.32 kg/s	m_{min} =0.7×6.571=4.6 kg/s
Maximum weir crest, $h_{wc} = 750\left(\frac{L_{wc}}{L_W \rho_l}\right)^{2/3}$ = $750\left(\frac{9.02}{1.752\times744}\right)^{2/3}$ =27.2 mm liquid height	$h_{wc} = 750\left(\frac{6.571}{1.752\times955}\right)^{2/3}$ =18.7 mm liquid height
Minimum weir crest, $h_{wc} = 750\left(\frac{L_{wc}}{L_W \rho_l}\right)^{2/3}$ = $750\left(\frac{6.32}{1.752\times744}\right)^{2/3}$ =21.5 mm liquid height	$h_{wc} = 750\left(\frac{4.6}{1.752\times955}\right)^{2/3}$ =14.7 mm liquid height
The constant (K_2) of weep-point correlation= 30.3 at $h_{wc} + h_w$ =40+21.5=61.5 mm using minimum liquid flow rate (**[3] page 571**).	K_2= 30.2at $h_{wc} + h_w$ =54.7
The minimum vapor velocity ($U_{\min}$) at the weep point: $U_{\min} = \frac{K_2 - 0.9(25.4-d_h)}{\rho_v{}^{1/2}} = \frac{30.3-0.9(25.4-12)}{(2.08)^{1/2}}$ =12.6 m/s	$U_{\min}$at the weep point: $U_{\min} = \frac{30.2-0.9(25.4-12)}{(0.693)^{1/2}}$ =21.8 m/s
Actual minimum vapor velocity at minimum vapor flow rate: $= \frac{\text{Actual vapor flow rate}}{A_H} = \frac{70\ \%\ \text{of}\ Q_{max}}{A_H} = \frac{0.7\times6.98}{0.489}$=10 m/s	$= \frac{0.7\times15.84}{0.489}$=22.7 m/s

Therefore, the minimum operating velocity both in top and bottom sections is of above the weep point velocity.

Step #8: Plate pressure drop (refer to section 7.4; Eqs. 7.7, 7.8 & 7.10)

Top section	**Bottom section**
Maximum vapor velocity: $U_{max} = \frac{Q_{max}}{A_H} = \frac{6.98}{0.489}$=14.3 m/s	$U_{max} = \frac{Q_{max}}{A_H} = \frac{15.84}{0.489}$=32.4 m/s
Maximum **dry plate pressure drop**: $h_d = 51\left(\frac{U_{max}}{C_0}\right)^2 \frac{\rho_v}{\rho_l} = 51\left(\frac{14.3}{0.88)}\right)^2 \frac{2.08}{744} = 37.5$ mm liquid [The orifice coefficient, C_0 =0.88 at $A_H/A_P = 15\%$ and $\frac{\text{plate thickness}}{\text{hole diameter}}$ =1 (**[3] page 576**).	$h_d = 51\left(\frac{32.4}{0.88)}\right)^2 \frac{0.693}{955} =$ 50.2 mm liquid
Residual head: $h_r = \frac{12.5\times10^3}{\rho_l} = \frac{12.5\times10^3}{744}$ =16.8 mm liquid	$h_r = \frac{12.5\times10^3}{\rho_l} = \frac{12.5\times10^3}{955}$ =13 mm liquid
Total plate pressure drop: $h_t = h_d + (h_{wc} + h_w) + h_r$ = 37.5 + (40+27.2)+16.8≈122 mm liquid	h_t = 50.2 + (40+18.7)+13≈122 mm liquid
The plate pressure drop of 1.25 kPa (=127 mm of water and 161 mm of acetone pressure) was assumed. The estimated value in the first trial is therefore acceptable.	

Step # 9: Downcomer backup liquid and downcomer residence time: (refer to section 7.4; Eqs. 7.11-7.13)

Downcomer back: $h_b = (h_{wc} + h_w) + h_t + h_{dc}$

Head loss in downcomer: $h_{dc} = 166\left(\frac{L_{wd}}{\rho_l A_m}\right)^2$

Downcomer liquid flow rate (L_{wd}) =maximum liquid flow rate is taken

A_m is smaller of A_{ap} and A_D.

$A_{ap} = h_{ap}\, l_w = 30\times10^{-3}\times1.752$ =0.0525 m^2 (typically $h_{ap} = h_w - 10$)

Here, $A_{ap} < A_D = 0.452$ m^2

Top section	**Bottom section**
$h_{dc} = 166\left(\frac{9.02}{744\times0.0525}\right)^2$ =8.8 mm	$h_{dc} = 166\left(\frac{6.571}{955\times0.0525}\right)^2$ =2.9 mm
$h_b = (27.2+40) + 122 + 8.8$ ≈198 mm	$h_b = (18.7+40) + 122 + 2.9$ ≈184 mm

Downcomer residence time: $t_{dt} = \frac{A_D h_{bc} \rho_l}{L_{wd}} = \frac{0.452 \times (184 \times 10^{-3}) \times 955}{6.571} \approx 12$ s >3 s. h_{bc} = clear liquid back up ($h_{bc} \approx h_b$ can be approximated)	$t_{dt} = \frac{0.452 \times (184 \times 10^{-3}) \times 955}{6.571} \approx 12$ s >3 s.
$\frac{1}{2}$(plate spacing + weir height) $= \frac{1}{2}(600 + 40) = 320$ mm $\frac{1}{2}$(plate spacing + weir height) $> h_d$ **Therefore, the plate spacing and downcomer residence time in both the sections meet the design required design criteria.**	

Lecture 6: Provisional Plate Design

Step #10: Calming zones and hole pitch (refer to sections7.6.2 &7.6.4; Eq. 7.15)

Perforated area (A_P): $A_P = A_A - A_{CZ} - A_{ES}$

Where, A_{CZ} = calming zone area (Figure 7.3).

A_{ES} = area occupied by edge strip (Figure 7.9)

$\frac{l_W}{D_T}$=0.73; now, θ_c = 95° **([3] page 573)**

Angle subtended by the chord (edge plate), α = 180°-95° = 85°

The unperforated edge strip (edge plate) mean length from the geometry:

l_{ES} =(D_T-50×10^{-3})×$\frac{\alpha \times \pi}{180}$=(2.4-50×10^{-3})×$\frac{85 \times \pi}{180}$=3.49 m

A_{ES} = 50×10^{-3}×l_{MS} =0.175 m^2

Use 50 mm wide calming zones. The approximate mean length of zones:

l_{CZ} =Weir length (l_W) + Width of unperfortaed edge strip

=1.752+50×10^{-3}=1.802 m

A_{CZ} = 2(50×10^{-3}×l_{CZ})= 0.18 m^2

Therefore, perforation area per tray (A_P) $= A_A - A_{CZ} - A_{ES}$ =3.616- 0.18-0.175= 3.26 m^2

Take total hole area $A_H = 0.15A_A = 0.489$ m^2

$A_H = 0.785 \times d_h^2 \times n_h = 0.489$ m^2 [hole diameter 12 mm]

Number of holes (n_h)= 4326

$A_H/A_P = 0.15$. For equilateral triangular pitch: $\frac{A_H}{A_P} = 0.907\left(\frac{d_h}{l_P}\right)^2$

This corresponds to hole-pitch to hole diameter ratio of (l_P/d_h) $= 2.46$. This is very close to the normal range of 2.5 to 4.0 times of hole diameter.

The estimated hole pitch (l_P)=is 29.5 mm.

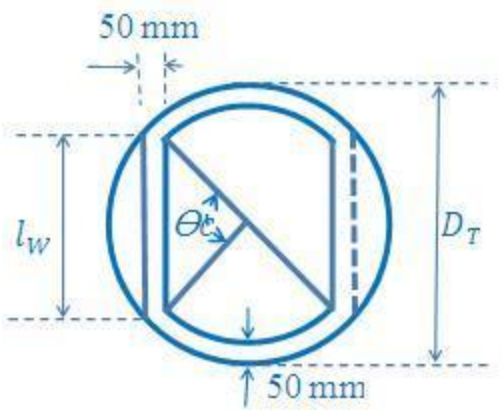

Figure 7.9. Angle subtended by the chord ([3] page 583).

Steps # 11 and 12: Entrainment checking (refer to section 7.3.3; Eq. 7.6)

Top section	**Bottom section**
Actual vapor velocity (U_v) based on net area (A_N) selected provisionally: $U_v = \frac{Q_{max}}{A_N} = \frac{6.98}{4.068} = 1.7$ m/s % flooding$=\frac{U_v}{U_{nf}} \times 100 = \frac{1.7}{2.26} \times 100 = 76$ % The **fractional entrainment**, Ψ=0.09 at $F_{LG} = \frac{L}{V}\left(\frac{\rho_v}{\rho_l}\right)^{0.5} = 0.033$ and actual flooding velocity of 76 % (**[4] page 14-28**). Effect of Ψ on Murphree plate efficiency can be estimated from (**[4] page 14-29**): $$E_a = \frac{E_{mv}}{1 + \frac{\Psi E_{mv}}{1-\Psi}} = 0.57$$ $E_{mv} = 0.6$ (Murphree vapor efficiency 60%) E_a=Murphree vapor efficiency, corrected for liquid entrainment	$U_v = \frac{Q_{max}}{A_N} = \frac{15.84}{4.068} = 3.9$ m/s % flooding$=\frac{U_v}{U_{nf}} \times 100 = \frac{3.9}{5.05} \times 100 = 77\%$ Ψ=0.18 at $F_{LG} = 0.016$ and actual flooding velocity of 77 % (**[4] page 14-28**). $E_a = 0.53$
The actual flooding is below the design flooding value of 80%. Usually, Ψ<0.1 is desirable. However, the optimum design value may be above this.	

Design problem: Absorption column

An industrial gas stream is available @ 2 kg/sfrom a cracking operation of NH_3containing 72% H_2, 24% N_2 and 4% $NH_3$by mole, at 202.65 kPa and 35°C.You have been asked to design a multistage countercurrent bubble cap absorber to remove NH_3 from the above stream with water as the scrubbing liquid. The liquid mass flow rate is limited to be 2 to 3.5 times of gas mass rate.NH_3concentration should not be greater than 0.003 mg per m^3 of the exit gas.

Assumptions/ design considerations:

- Lean water-NH_3 system follows Henry's law and the corresponding equilibrium relation: $y^* = 0.85x$ @30°C
- Isothermal gas absorption at room temperature (~30°C)
- Optimum adsorption factor (A)= 1.2 to 2
- Overall column efficiency=70%
- Pressure drop per plate= 1 kPa
- Minimum liquid loading=70% of expected maximum loading

Hints: The flow rates of liquid and gas entering and leaving the absorber is almost constant thought out the column if a small amount of the solute gas is absorbed. This is a typical case, also common in practice when the solute gas concentration in the feed stream is low (dilute gas absorption). For such operations, the variation of temperature between column top and bottom trays is insignificant (~isothermal operation). The pressure drop, if the column is not too tall, has minor effect on the physical properties of process fluids that could influence the column design. The section-wise determination of number trays and design are performed if the gas stream and/ or the solvent liquid (usually makeup solvent) are introduced at any intermediate point of the column. The number of theoretical trays can be estimated using either Kremser equation or graphical technique for multistage counter current lean gas absorption (**[1] page 290**). The vapor loading is the highest at the bottom tray even though its variation is not appreciable. For the safe side, the design is usually performed at the bottom tray.

The mole fractions (x,y) between the phases are plotted in McCabe Thiele method of distillation calculation. In case of absorption, the mole ratios ($X = \frac{x}{1-x}$, $Y = \frac{y}{1-y}$) are used for the determination of number of trays in graphical method instead of mole fractions.

References

[1]. Robert E. Treybal, Mass Transfer Operations, McGraw-Hill, Inc., 3rd ed. 1981.
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[3]. R. K. Sinnott, Coulson & Richardson's Chemical Engineering: Chemical Engineering Design (vol. 6), Butterworth-Heinemann, 3rd ed. 1999.
[4]. Perry's Chemical Engineers' Handbook, McGraw-Hill Companies, 7th ed. 1997.
[5]. Henry Z. Kister, Distillation Design, McGraw-Hill, Inc., 1st ed. 1992.