CHE 211 – EQUIPMENT DESIGN

PROJECT REPORT

GROUP NO. 6

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TABLE OF CONTENTS

<u>PROCESS DESIGN OF DISTILLATION COLUMN</u>

Introduction

Design of plate column for distillation involves many steps of calculation such as determination of number of theoretical plates, column diameter, plate hydraulic design, etc. The separation in distillation is based on the relative volatility of the components. Additional vapour 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.

Plate Columns

Plate columns/ towers are vertical cylindrical columns in which a vertical stack of trays or plates are installed across the column height as shown in Figure 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/vapour 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/vapour-liquid) takes place across the tray and through the column in a stage-wise manner.

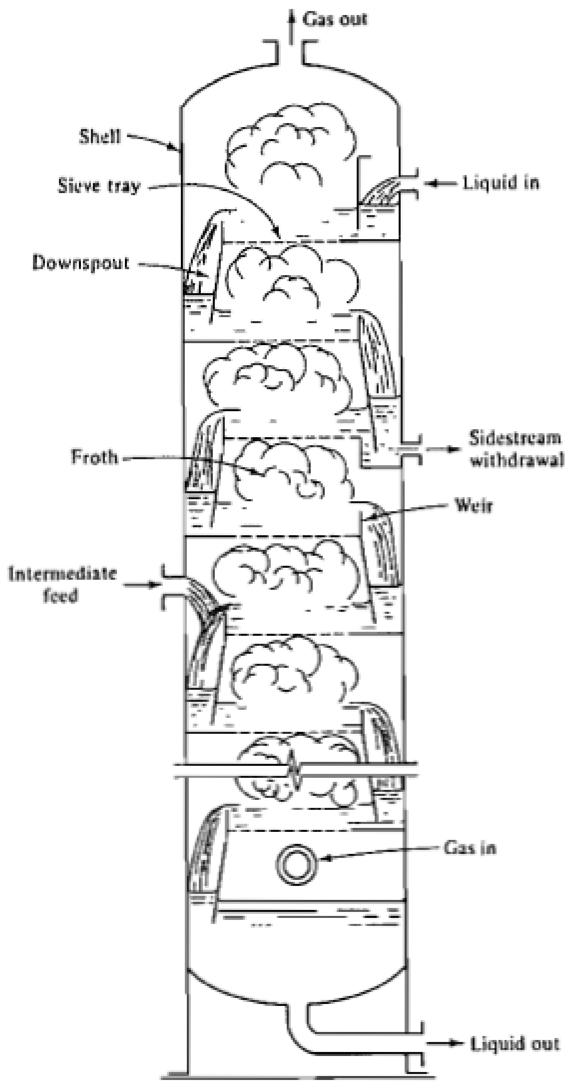


FIG. 1- Schematic diagram of a plate column

Selection of plate type

There are many types of plate designs like Bubble cap, valve and sieve trays. The principal factors which we must bear in mind before selecting the plate type are – Cost, Capacity, Operating range, Efficiency and pressure drop.

Sieve trays are the least expensive and suitable for almost all applications. We have selected sieve trays in our distillation column due to its following characteristics –

- Capacity- High capacity among other plate types

- Efficiency – High
- Pressure drop – Medium
- Entrainment – Medium
- Turndown ratio – 2.1
- Cost – Cheapest of all plate types [one of the crucial factors]

Sieve plate

The sieve tray (also known as perforated plate) is a flat perforated metal sheet. The sieve tray layout is a typical equilateral triangular pitch holes. The gas/vapour 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.

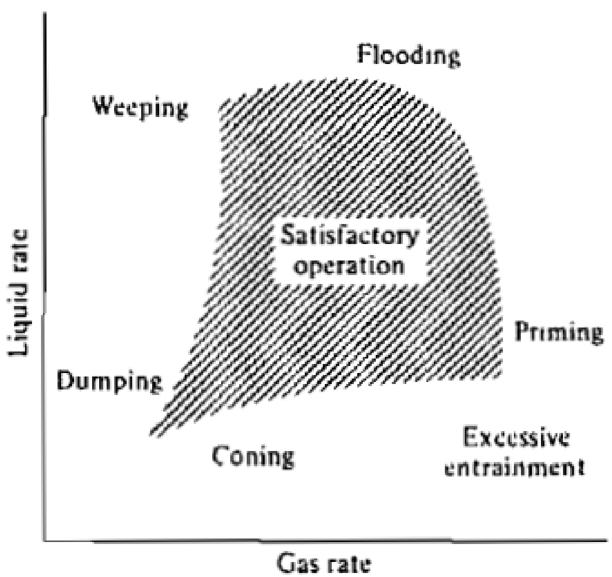


FIG 4- Operating characteristics of sieve trays

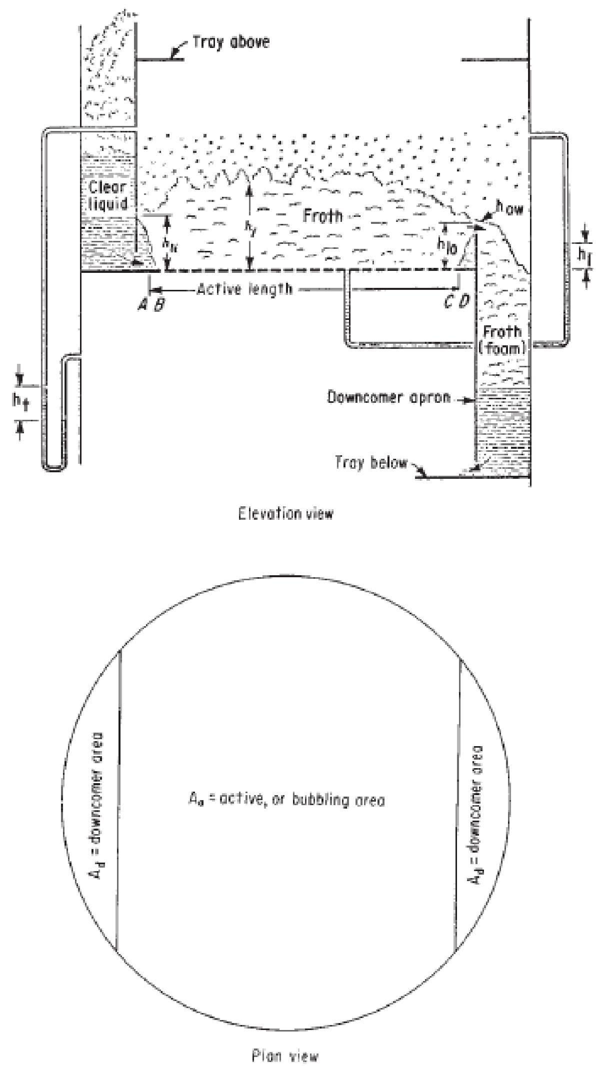


FIG 3- Sieve plate diagram

Plate Hydraulic design

There are certain basic requirements for plate design, which are given below –

- Provide good vapour liquid contact
- Provide sufficient liquid hold-up for good mass transfer between the phases
- Have sufficient area and spacing to keep entrainment and pressure drop within the acceptable limits
- Have sufficient downcomer area for liquid to flow freely from plate to plate

Plate design, like many other types of engineering design, is a blend of theory and practice. There are several empirical and semi-epirical equations and correlations which help us to find certain parameters of designing of the sieve plates, combined with the experience of operating real-life distillation columns thereby providing recommended limits for designing of different hydraulic variables associated with the design.

Stepwise design tray procedure

Plate design is trial and error based, i.e. it is iterative in such a way that we start with certain assumptions and then check key performance parameters which are critical for the proper functioning of the tower, and revise the parameters successively. A typical design procedure is set out as shown –

Step #1: Determine the number of theoretical plate and vapour 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).

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

Next, we move on to solve for process designing of the distillation column according to our problem statement.

Problem Statement

Problem No. 9.15 from Mass Transfer Operations by Robert Treybal –

A solution of carbon tetrachloride and carbon disulphide containing 50 % each is to be continuously fractionated at standard atmospheric pressure at flowrate of 4000 kg/h. The distillate product is to contain 95 wt% of carbon disulphide, the residue 0.5%. The feed will be 30 mol% vaporized before it enters into the column. A total condenser will be used and reflux will be returned at bubble point.

<u>VLE data for carbon disulphide</u>

x	0	0.0296	0.0615	0.1106	0.1435	0.2585	0.3908	0.5318	0.6630	0.7574	0.8604	1.000
y	0	0.0823	0.1555	0.2660	0.3325	0.4950	0.6340	0.7470	0.8290	0.8780	0.9320	1.000
T, ºC	76.7	74.9	73.1	70.3	68.6	63.8	59.3	55.3	52.3	50.4	48.5	46.3

(a) Determine product rates, in kg/h.

(b) Determine minimum reflux ratio.

(c) Determine minimum number of trays graphically.

(d) Determine number of theoretical trays at reflux ratio of twice the minimum reflux ratio and the position of the feed tray.

(e) Estimate overall tray efficiency of sieve tray tower of conventional design and the number of real trays.

(f) Determine enthalpy of feed, products and vapour entering the condenser. Determine heat loads of condenser and reboiler.

The Process design steps are evaluated in detail as follows –

Step #1: **<u>Mass balance and determination of number of theoretical stage</u>**

Component	Feed Mole fraction	Top product mole fraction	Bottom product mole fraction
Carbon Disulfide	0.67	0.97	0.01
Carbon tetrachloride	0.33	0.03	0.99

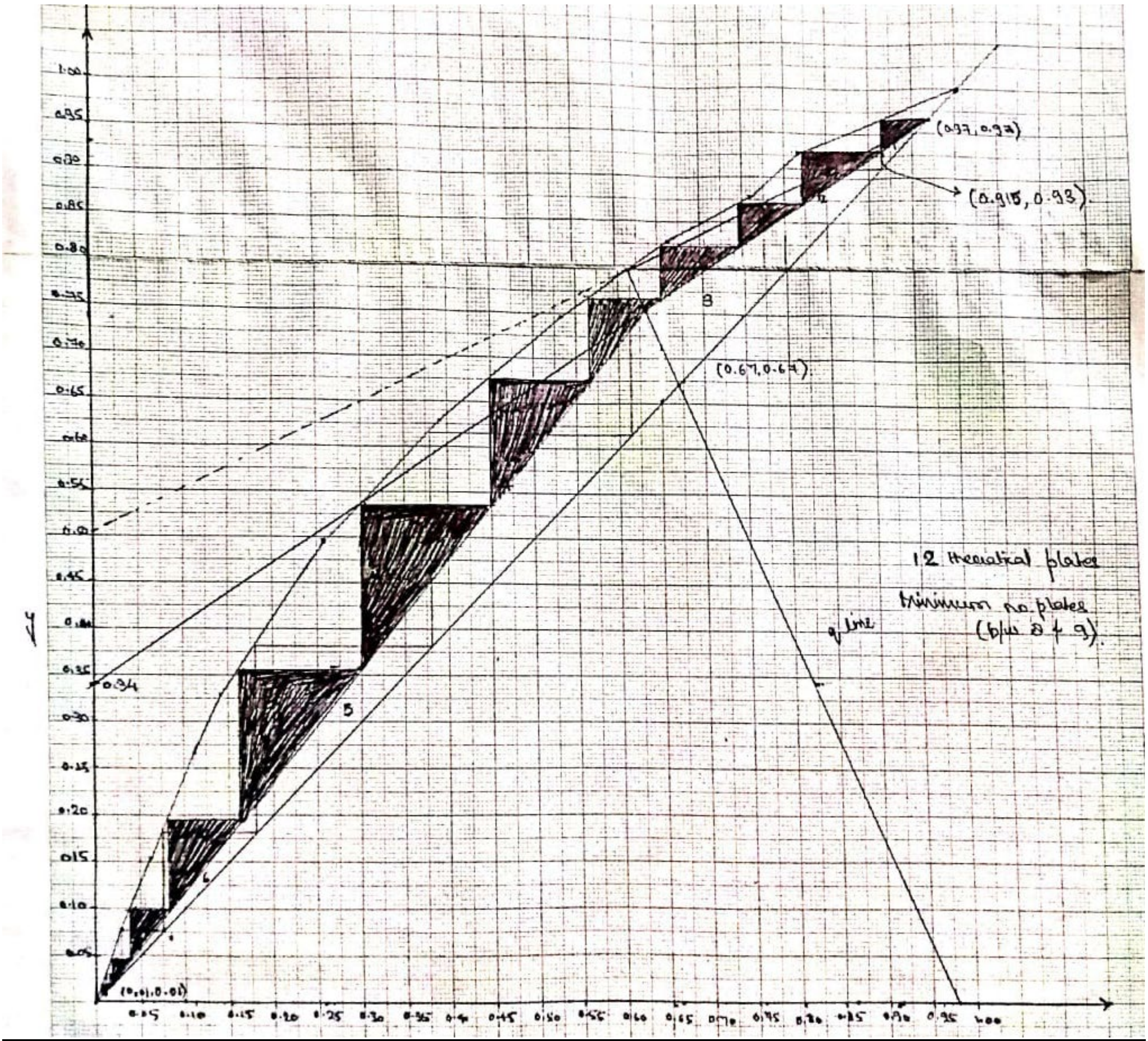


FIG. 5 – Hand-drawn McCabe-Thiele diagram for determining the theoretical number of plates, minimum reflux ratio, feed tray location

q=0.70 (given)

From the Figure 5

Intercept on the y-axis of the line joining the point(x_D, x_D) and the point obtained by intersection of q-line and equilibrium curve gives the value of R_{min}.

$\frac{x_D}{R_{min}+1}$ =0.505; R_{min} =0.92 for x_D=0.97

Here, **reflux ratio**, R=2×Rmin =2×0.92= 1.84 is taken for this design.

Average molecular wt. of feed= 0.67×76.139 + 0.33×153.82=101.77 g/mol.

Molar feed flow (F) rate=4000/101.77=39.30 kmol/h

Carbon disulfide balance: (D × 0.97) + (39.30-D) x 0.01= 39.30 x 0.67⇒D = 27.01875 kmol/h

Vapour flow (V) rate above feed plate, $V = D\ (1 + R)$ = 27.01875 + 49.7145= 76.73325

kmol/h

(Assuming constant molar overflow)

Top section liquid flow rate, $L = V - D$ = 49.7145 kmol/h

Bottom product: $B = F - D$ = 39.03 – 27.01875 = 12.28125 kmol/h

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

L'= Liquid flow rate below feed plate = L + q x F=49.7145 + 0.70 x 39.30= 77.2245 kmol/h

V'= Vapour flow rate below feed plate = 64.94325kmol/h

The construction of operating lines and number of theoretical stages are shown in Fig 5.

Total number of tray= 4 (above feed) +9 (below feed) =12.5

Total number of real stages= (12.5-1)/0.6≈ 20 (60% column efficiency; reboiler was considered as equivalent to one theoretical tray)

$\therefore$ Total number of ideal trays = 12.5 and real trays = 20

Step #2: **<u>Estimation of physical properties</u>**

<table>
<tr><td colspan="2">Column top pressure= 101325 Pa (1 atm)
Column pressure drop=1.5×103×20=131325 kPa … Pressure drop of 1.5 kPa per tray is assumed</td></tr>
<tr><td>Top section:</td><td>Bottom section:</td></tr>
<tr><td>Column top pressure= 101325 Pa (1.0147 bar) and temperature= 56.3 °C
$$\rho_v = \frac{PM}{RT}$$
$$=\frac{101325 * 79.63}{8.314 * 1000 * 321.5}$$
$$= 3.018\ kg/m^3$$
ρ_l =1260 kg/m3 (density of the mixture)
(Carbon tetrachloride density = 1537 kg/m^3 and Carbon disulfide density= 1250 kg/m^3 at 48.5 °C)
Average molecular weight of vapour:
M=79.63</td><td>Column bottom pressure=101325 +16800 = 131325 Pa (=1.19 bar)
Average molecular weight of vapour:
M=149
Average molecular weight of liquid:
M=152

ρ_v = 6.53 kg/m^3

ρ_l =1461 kg/m3

Surface tension, σ =2.4 x 10^{-3} N/m</td></tr>
</table>

Average molecular weight of liquid: M=78.47 Surface tension, σ =2.6 x 10^{-3} N/m	

Step #3: **Plate spacing:**

Plate spacing of 450 mm is considered for the first trial to calculate capacity parameter (C_{sbf}) for the estimation of maximum allowable vapour velocity through the net plate area. The suggested plate spacing is 450 mm for column diameter < 1m.

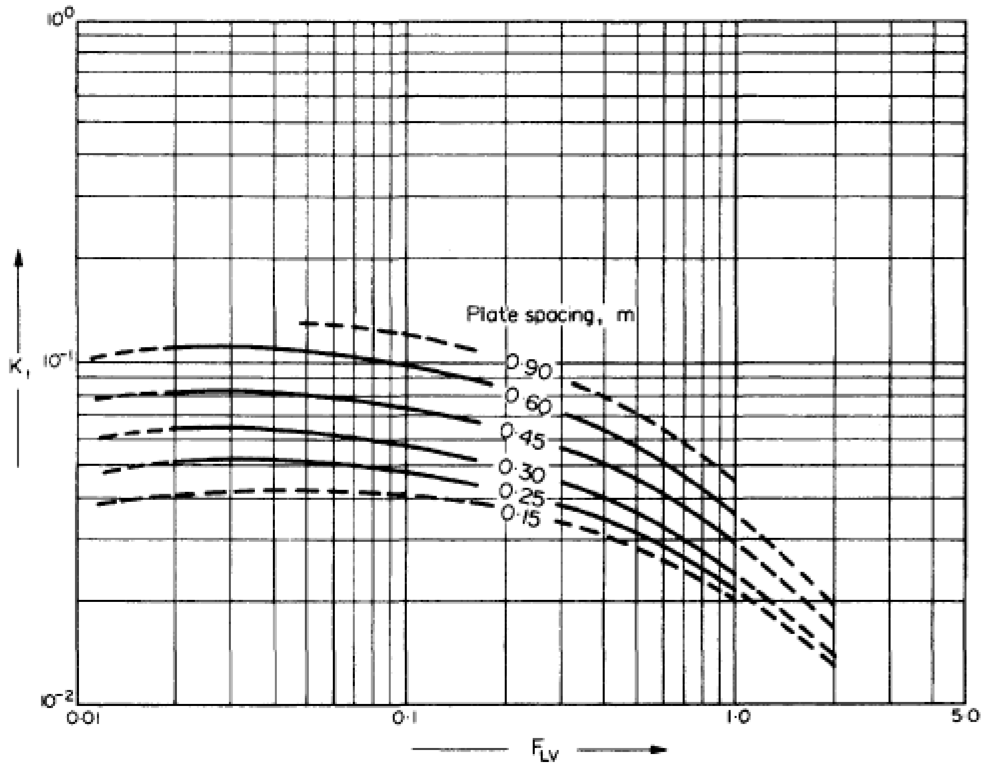


FIG 6 – Flooding velocity, Sieve trays

Step #4: **Column diameter:**

<table>
<tr><td colspan="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.</td></tr>
<tr><td>Top section:</td><td>Bottom section:</td></tr>
<tr><td>Flow parameter (F_{LG}) based on mass flow rate,
$\frac{L}{V}\left(\frac{\rho_v}{\rho_l}\right)^{0.5} = \frac{49.7}{76.7}\left(\frac{3.018}{1260}\right)^{0.5}$ =0.0316

Capacity parameter (C_{sbf}) =0.09 m/s

Gas velocity through the net area at flooding:</td><td>Flow parameter (F_{LG}) based on mass flow rate,
$\frac{L'}{V'}\left(\frac{\rho_v}{\rho_l}\right)^{0.5} = \frac{77.2}{64.9}\left(\frac{6.537}{1461}\right)^{0.5}$ =0.079

Capacity parameter (C_{sbf}) =0.082 m/s

Gas velocity through the net area at flooding:</td></tr>
</table>

$U_{nf} = C_{sbf}(\frac{\sigma}{20})^{0.5}(\frac{\rho_l - \rho_v}{\rho_l})^{0.5}$=0.09 x $(\frac{26}{20})^{0.5}(\frac{1260-3.018}{3.018})^{0.5}$ =1.94 m/s. [σ = liquid surface tension, mN/m] The linear design gas velocity (U_n) based on net area (80% flooding): U_n=0.8×1.94=1.55 m/s. The maximum volumetric vapour flow rate (Q_{max}): $Q_{max} = \frac{V*M}{\rho_v} = \frac{76.7*79.63}{3.018}$ =0.5621 m^3/s. Net area required: $\frac{Q_{max}}{U_n} = \frac{0.5621}{1.55}$=0.34 m^2 Totals tower cross-section area: 0.34/0.9=0.3626 m^2 (Total downcomer top and bottom seal area is 10% of the net area) Column (tower) diameter : $(\frac{0.3626}{0.785})^{0.5} = 0.716$ m	$U_{nf} = C_{sbf}(\frac{\sigma}{20})^{0.5}(\frac{\rho_l - \rho_v}{\rho_l})^{0.5}$=0.09 x $(\frac{24}{20})^{0.5}(\frac{1461-6.537}{6.537})^{0.5}$ =1.272 m/s. [σ = liquid surface tension, mN/m] The linear design gas velocity (U_n) based on net area (80% flooding): U_n=0.8×1.272=1.017 m/s. The maximum volumetric vapour flow rate (Q_{max}): $Q_{max} = \frac{V*M}{\rho_v} = \frac{64.9*149}{6.537}$ =0.412 m^3/s. Net area required: $\frac{Q_{max}}{U_n} = \frac{0.412}{1.017}$=0.0.42 m^2 Totals tower cross-section area: 0.42/0.9=0.47 m^2 (Total downcomer top and bottom seal area is 10% of the net area) Column (tower) diameter : $(\frac{0.47}{0.785})^{0.5} = 0.757$ m
We here will use the higher value of diameter as the diameter of the column, to maintain uniformity. **The nearest recommended shell (nominal diameter 800 mm) fabricated from carbon steel is as per IS 2844-1964.**	

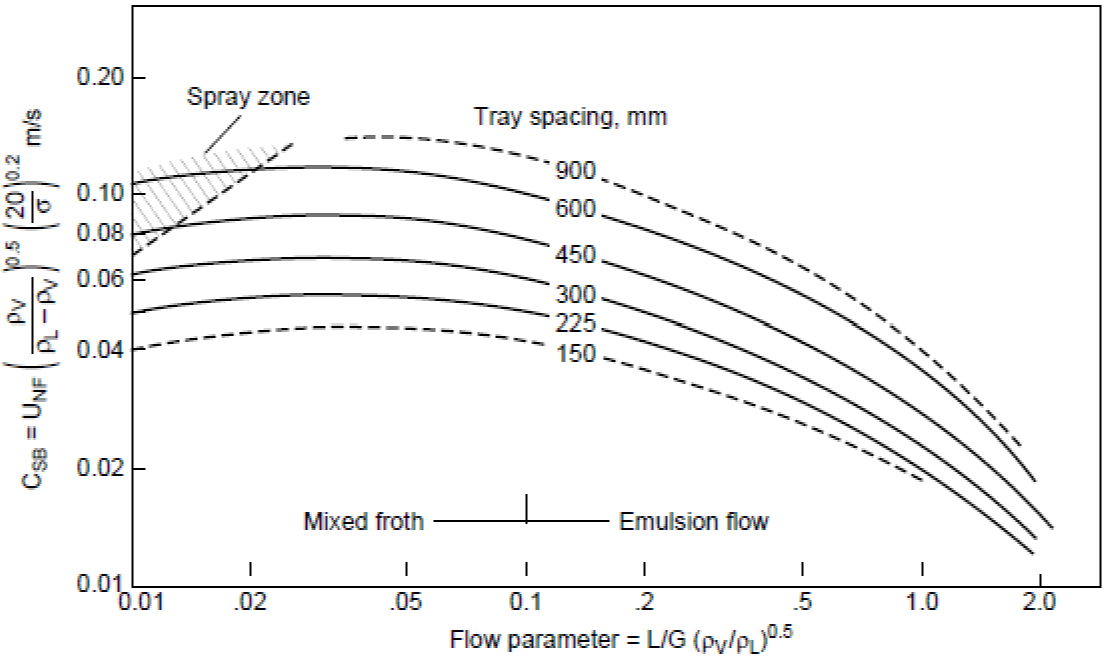


FIG 7 - Flooding correlation for columns with cross flow sieve plates

IS : 2844 - 1964

3. NOMINAL DIAMETERS

3.1 The recommended nominal diameters shall be as given in Table 1.

TABLE 1 NOMINAL DIAMETERS

100	600	(1 500)	2 400	(4 250)
125	700	1 600	2 600	4 500
150	800	(1 700)	2 800	(4 750)
200	900	1 800	3 000	5 000
250	1 000	(1 900)	3 200	
300	1 100	2 000	(3 400)	
(350)	1 200	(2 100)	3 600	
400	(1 300)	2 200	(3 800)	
500	1 400	(2 300)	4 000	

NOTE — Values given in the brackets are second preference values.

Step #5: **Selection of liquid-flow arrangement**

Liquid volumetric flow rate in the top section $=\frac{49.7145\ \text{x}\ 78.47}{3600\ x\ 1260}$=0.00086 m^3/s

Liquid volumetric flow rate in the bottom section $=\frac{77.2\ x\ 152}{3600\ x\ 1461} = 0.00223\ m^3/s$

Therefore, single pass cross-flow sieve plate is chosen for this service.

Step #6: **Provisional plate design**

Column (tower) diameter (ID): $D_T \approx 0.8$ m

Column cross-section area: $A_T = 0.785 \times D_T^2 = 0.5024\ m^2$

Downcomer area: $A_D = 0.1A_T = 0.05024\ m^2$

Net area: $A_N = A_T - A_D = 0.45216\ m^2$

Weir Length (l_W) = $0.73 \times D_T = 0.584$ m

Weir height, h_w= 40 mm is considered.

Active area: $A_A=A_T-2\times A_D$ =0.40192 m^2

Preferred hole size is 5 mm. Holes may be drilled or punched, as punching is cheaper, we will prefer that. As per recommendations from Coulson and Richardson's Chemical Engineering Design Vol. 6, for material of carbon steel, hole sizes approximately equal to plate thickness can be punched. This is exactly what we have implemented in the designing. For the first trial, consider hole diameter: d_h=4 mm. The plate thickness=hole diameter is selected for the first trial.

Step #7: **<u>Weeping considerations</u>**:

Top section:	**Bottom section:**
Maximum liquid flow rate (m_{max})= $\frac{49.7\ x\ 79.63}{3600}=1.08\ kg/s.$	Maximum liquid flow rate (m_{max})=$\frac{77.2\ x\ 152}{3600}=3.26\ kg/s.$
Minimum liquid flow rate (m_{min}) (70% of m_{max})=0.7×1.08=0.756 kg/s	Minimum liquid flow rate (m_{min}) (70% of m_{max})=0.7×3.26=2.282 kg/s
Maximum weir crest, $h_{wc}=750\ (\frac{Lwc}{\rho_l\ x\ Lw})^{2/3}=750\ (\frac{1.08}{1260\ x\ 0.584})^{2/3}$=9.69 mm liquid height	Maximum weir crest, $h_{wc}=750\ (\frac{Lwc}{\rho_l\ x\ Lw})^{2/3}=750\ (\frac{3.26}{1461\ x\ 0.584})^{2/3}$=18.33 mm liquid height
Minimum weir crest, , $h_{wc}=750\ (\frac{Lwc}{\rho_l\ x\ Lw})^{2/3}=750(\frac{0.756}{1260\ x\ 0.584})^{2/3}$=7.64 mm liquid height	Minimum weir crest, , $h_{wc}=750\ (\frac{Lwc}{\rho_l\ x\ Lw})^{2/3}=750(\frac{2.282}{1461\ x\ 0.584})^{2/3}$=14.44 mm liquid height
The constant (K_2) of weep-point correlation= 29.8 at $h_{wc}+h_w$=40+7.64=47.64 mm using minimum liquid flow rate. The minimum vapour velocity (U_{min}) at the weep point: $U_{min}=\frac{K_2-0.9(25.4-d_h)}{\rho_v{}^{1/2}}=\frac{29.8-0.9(25.4-4)}{3.018^{1/2}}$=6.06 m/s. Actual minimum vapour velocity at minimum vapour flow rate: $=\frac{\text{Actual vapour flow rate}}{A_H}=\frac{70\ \%\ of\ Q_{max}}{A_H}=\frac{0.70\ x\ 0.5623}{0.040192}$ =9.79 m/s.	The constant (K_2) of weep-point correlation= 30.3 at $h_{wc}+h_w$=40+14.44=54.44 mm using minimum liquid flow rate. The minimum vapour velocity (U_{min}) at the weep point: $U_{min}=\frac{K_2-0.9(25.4-d_h)}{\rho_v{}^{1/2}}=\frac{30.3-0.9(25.4-4)}{6.537^{1/2}}$=4.32 m/s. Actual minimum vapour velocity at minimum vapour flow rate: $=\frac{\text{Actual vapour flow rate}}{A_H}=\frac{70\ \%\ of\ Q_{max}}{A_H}=\frac{0.70\ x\ 0.412}{0.040192}$ =7.17 m/s.

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

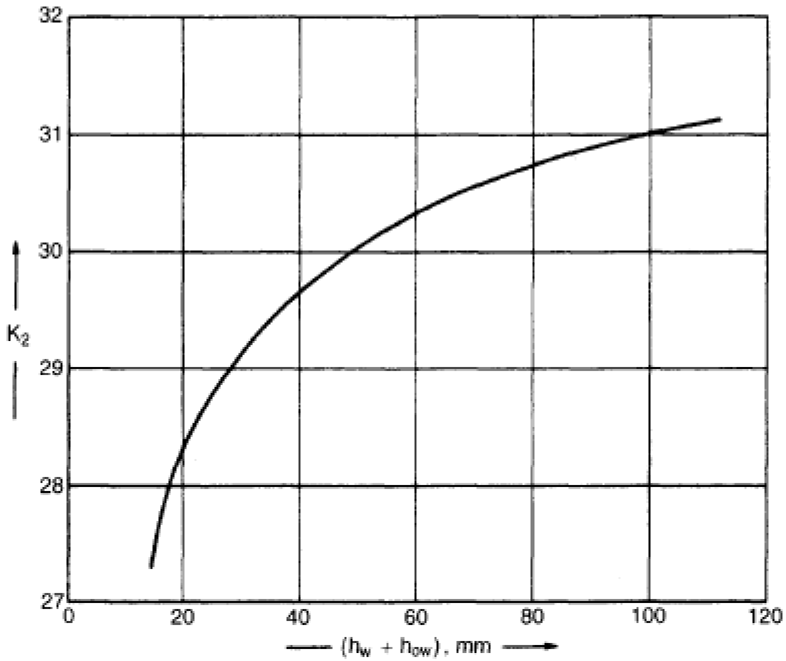


FIG 8 – Weep point correlation

Step #8: **Plate pressure drop**

Top section:	**Bottom section:**
Maximum vapour velocity: $U_{max}=\frac{Q_{max}}{A_H}=\frac{0.5623}{0.040192}$=13.98 m/s.	Maximum vapour velocity: $U_{max}=\frac{Q_{max}}{A_H}=\frac{0.412}{0.040192}$=10.25 m/s.
Maximum dry plate pressure drop $h_d = 51\left(\frac{U_{max}}{C_o}\right)^2\left(\frac{\rho_v}{\rho_l}\right)$=33.83 mm liquid	Maximum dry plate pressure drop $h_d = 51\left(\frac{U_{max}}{C_o}\right)^2\left(\frac{\rho_v}{\rho_l}\right)$=33.94 mm liquid
Residual head : $h_r = \frac{12.5 \times 10^3}{\rho_l}=\frac{12.5 \times 10^3}{1260}$=9.92 mm liquid	**Residual head** : $h_r = \frac{12.5 \times 10^3}{\rho_l}=\frac{12.5 \times 10^3}{12601461}$=8.55mm liquid
Total plate pressure drop: $h_t=h_d+h_{wc}+h_w+h_r$= 33.83 + (40+9.69)+9.92≈93.14 mm liquid	Total plate pressure drop: $h_t=h_d+h_{wc}+h_w+h_r$= 33.94 + (40+18.33)+8.55≈100.82 mm liquid

The plate pressure drop of 1.5 kPa (=120 mm of carbon disulfide and 103 mm of carbon tetrachloride pressure) was assumed. The estimated value in the first trial is therefore acceptable

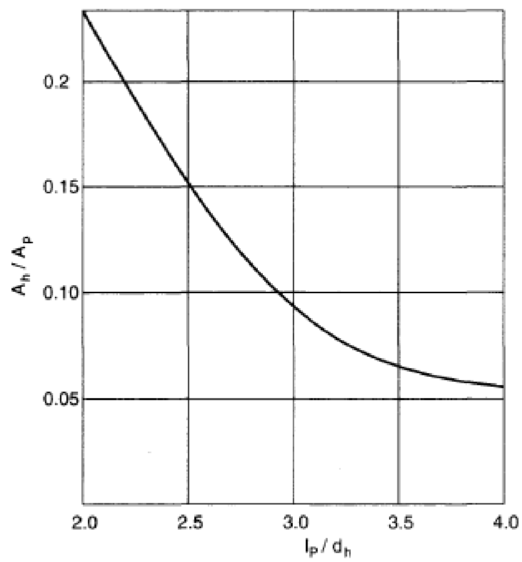


FIG 9 – Relation between hole area and pitch

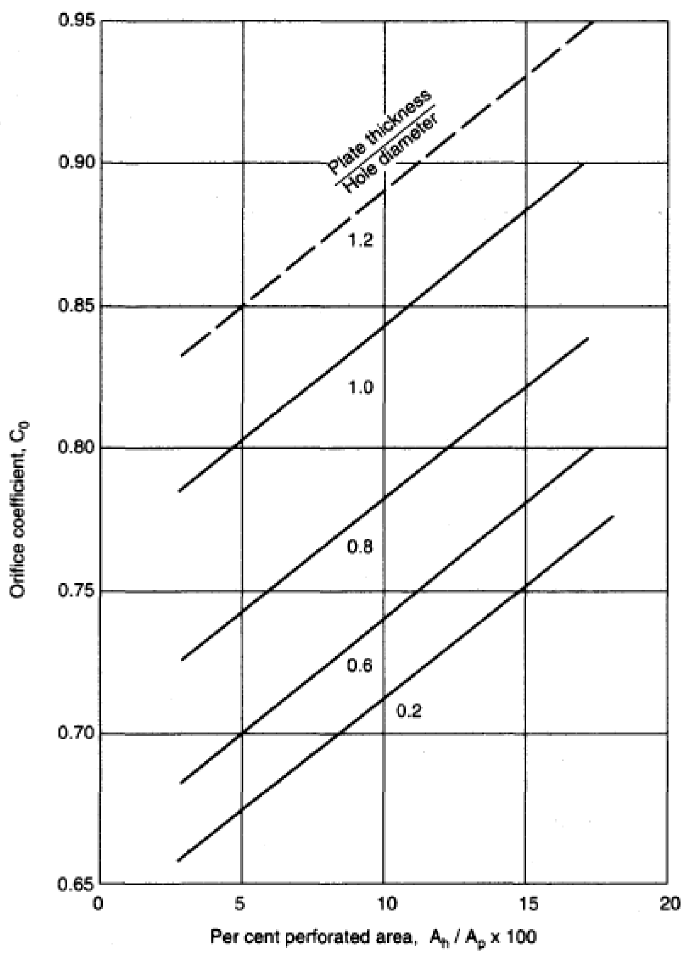


FIG 10 – Discharge coefficient, sieve plates

Step #9: **<u>Downcomer backup liquid and downcomer residence time</u>**

Downcomer back: : h_b=h_{dc}+(h_{wc}+h_w)+ h_t
Head loss in downcomer: h_{dc}=166 $\left(\frac{L_{wd}}{\rho_l \times A_m}\right)^2$
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 =30×10^{-3}× 0.584 =0.01752 m2 (typically h_{ap}=h_w−10)
Here, A_{ap} <A_D=0.05024 m2

Top section:	**Bottom section:**
h_{dc}=166 $\left(\frac{1,08}{1260 \times 0.01752}\right)^2$=0.365 mm h_b=0.365+(40+9.69)+93.14=143 mm Downcomer residence time: t_{dirt}=$\frac{A_D \times h_b \times \rho_l}{L_{wd}}$=$\frac{0.05024 \times 143 \times 10^{-3} \times 1260}{1.08}$=8.746 s > 3 s	h_{dc}=166 $\left(\frac{3.26}{1461 \times 0.01752}\right)^2$=2.69 mm h_b=2.69+(40+18.33)+100.82=161 mm Downcomer residence time: t_{dirt}=$\frac{A_D \times h_b \times \rho_l}{L_{wd}}$=$\frac{0.05024 \times 161 \times 10^{-3} \times 1461}{3.26}$ =3.46s > 3 s

$\frac{1}{2}$ (plate spacing + weir height) =12 (600+40) =250 mm

$\frac{1}{2}$ (plate spacing + weir height) > h_b

Therefore, the plate spacing and downcomer residence time in both the sections meet the design required design criteria.

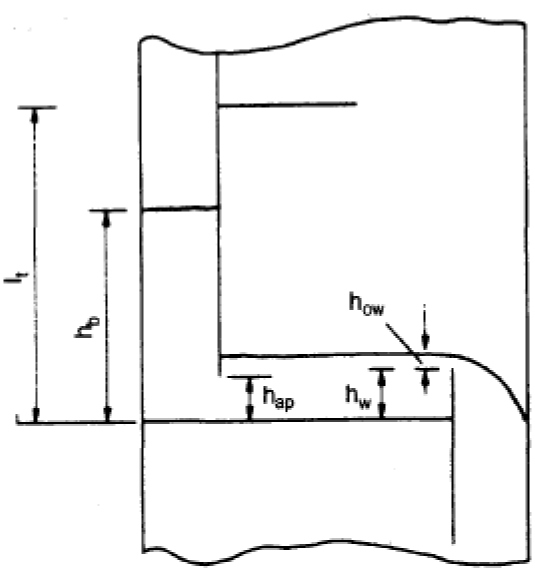


FIG 11 – Downcomer backup

Step #10: **<u>Calming zones and hole pitch</u>**

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

Where, A_{CZ} = calming zone area

A_{ES} = area occupied by edge strip

$\frac{l_W}{D_T}$=0.73; now, θ_c= 95°

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

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

$l_{ES} = (D_T - 50 \text{ x } 10^{-3}) \text{ x } \frac{\alpha \text{ x } \pi}{180}$ =1.112 m

A_{ES}= $50 \text{ x } 10^{-3} \text{ x } l_{ES}$=0.0556 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

=0.584+50×10-3=0.634 m

A_{CZ}= 2 x ($50 \text{ x } 10^{-3} \times l_{CZ}$)= 0.0634 m^2

Therefore, perforation area per tray A_P): $A_P = A_A - A_{CZ} - A_{ES}$ =0.40192-0.0634-0.0556= 0.28292 m^2

A_H=0.10 x A_A=0.040192 m^2

A_H=0.785 x $d_h{}^2$ x n_h= 0.040192 m^2

n_h = Number of holes = 3200

$\frac{A_H}{A_P} = 0.142$. For equilateral triangular pitch: $\frac{A_H}{A_P}$ = 0.907 $(\frac{d_h}{I_P})^2$

This corresponds to hole-pitch to hole diameter ratio of $(\frac{I_P}{d_h})$ = 2.52. This is very close to the normal range of 2.5 to 4.0 times of hole diameter.

The estimated hole pitch (I_P) =10.08 mm.

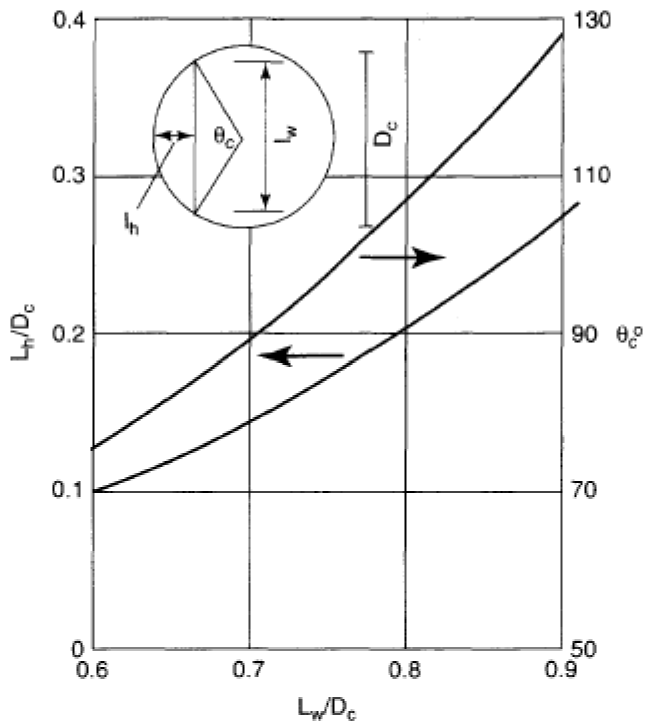


FIG 12 – Relation between angle subtended by chord, chord height and chord length

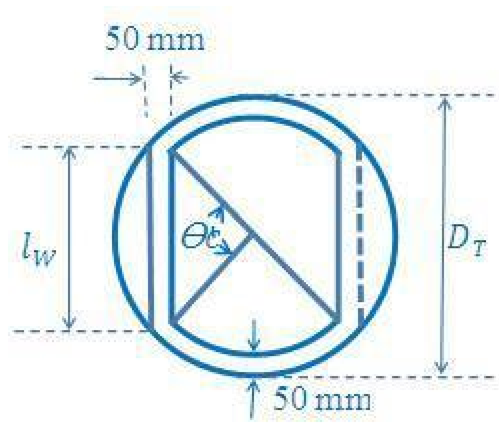


FIG 13 - Angle subtended by the chord

Step #11 and Step #12: **Entrainment checking**

Top section:	**Bottom section:**
Actual vapour velocity (U_v) based on net area (A_N) selected provisionally: $$U_v = \frac{Q_{max}}{A_N} = \frac{0.5623}{0.45216} = 1.243\ m/s$$ % flooding=$\frac{U_v}{U_{nf}}$×100=$\frac{1.243}{1.94}$×100=64 %	Actual vapour velocity (U_v) based on net area (A_N) selected provisionally: $$U_v = \frac{Q_{max}}{A_N} = \frac{0.412}{0.45216} = 0.9111\ m/s$$ % flooding=$\frac{U_v}{U_{nf}}$×100=$\frac{0.9111}{1.94}$×100=71.6 %

The fractional entrainment, Ψ=0.04 at $F_{LG}=\frac{L}{V}\left(\frac{\rho_v}{\rho_l}\right)^{0.5}$ =0.0316 and actual flooding velocity of 64 % Effect of Ψ on Murphree plate efficiency can be estimated from: $E_a=\frac{E_{mv}}{1+\frac{\Psi E_{mv}}{1-\Psi}}$=0.58 E_{mv}=0.6 (Murphree vapor efficiency 60%) E_a=Murphree vapour efficiency, corrected for liquid entrainment	The fractional entrainment, Ψ=0.03 at $F_{LG}=\frac{L}{V}\left(\frac{\rho_v}{\rho_l}\right)^{0.5}$ =0.79 and actual flooding velocity of 71.6 % Effect of Ψ on Murphree plate efficiency can be estimated from: $E_a=\frac{E_{mv}}{1+\frac{\Psi E_{mv}}{1-\Psi}}$=0.59 E_{mv}=0.6 (Murphree vapor efficiency 60%) E_a=Murphree vapour efficiency, corrected for liquid entrainment
The actual flooding is below the design flooding value of 80%. Usually, Ψ<0.1 is desirable, and we have obtained it.	

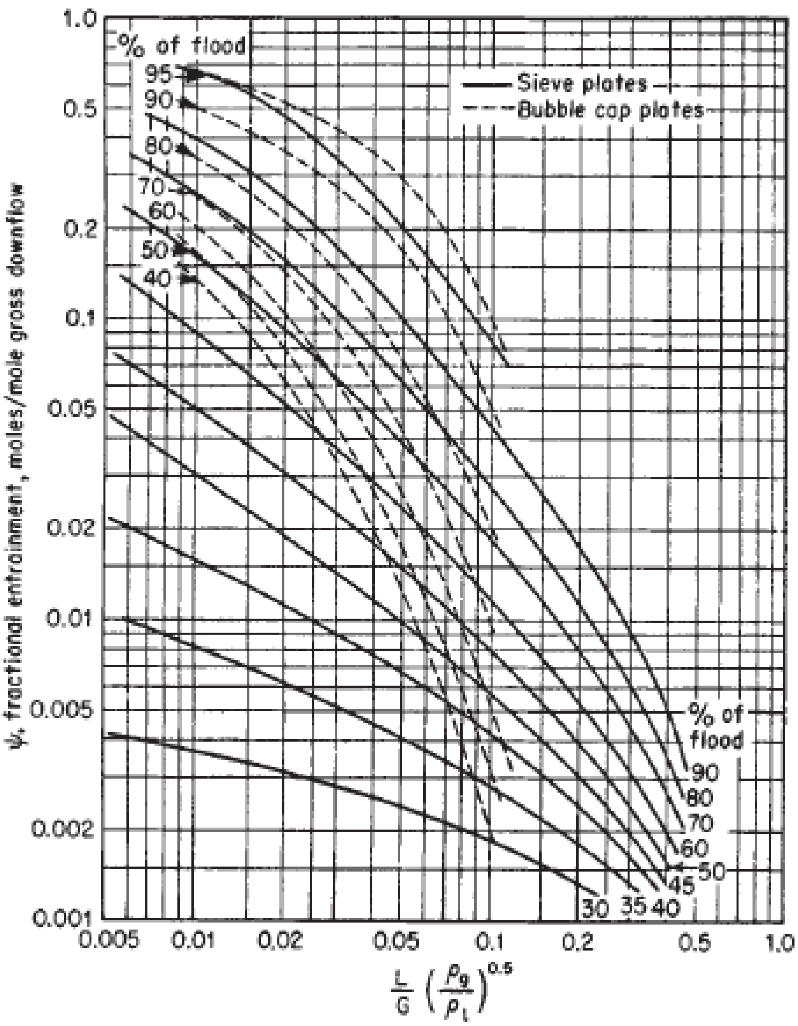


FIG 14 – Entrainment correlation

Thus, Process design of the Distillation column has been completed successfully. The findings have been given below –

- Number of theoretical stages = 12, Number of real stages = 20; taking overall efficiency of 60% for sieve tray columns
- Minimum reflux ratio = 0.92
- Tray spacing = 450 mm
- Diameter of column = 800 mm (Nominal Diameter according to IS 2503 1967)
- Plate thickness = Hole diameter = 4 mm
- Estimated value of Pressure drop per tray of 1.5 kPa is accepted
- Flooding, weeping and entrainment have been checked and are acceptable as per design procedures
- Triangular pitch, estimated hole pitch = 10.08 mm

MECHANICAL DESIGN OF DISTILLATION COLUMN

Upon completion of Process designing of the Distillation column, chemical engineers proceed to perform Mechanical designing. This involves calculation of stresses due to various factors in pressure vessels, and also due to wind and seismic effects which are very critical in the design of a tall equipment, such as the distillation column. In process design, we evaluate the details of the column such as the number of stages, the diameter of the column, its height, and pressure drop calculations, including considerations for flooding, weeping, entrainment, etc. for the proper functioning of the column. It is very important now for us to answer the following :

- What is the minimum thickness of the shell we require?
- What type of head should we use and what would be its minimum thickness ?
- What will be the material of construction we will be using for the column ? Will it be a single material for the entire column or should we have different materials for different sections/components ?
- What will be the thickness of insulation and its material of construction ?
- What is the magnitude of the axial and the circumferential stresses?
- What is the value of the compressive stresses caused by total dead loads in the column ?
- What is the value of the stresses developed due to wind and seismic effects?
- Is the maximum allowable stress for the material of construction much greater than the maximum possible total stresses for the column i.e. can we be sure that the column will remain safe from stresses due to various agents ?

These are the questions whose answers we will unravel as we move on into Mechanical designing of the distillation column !

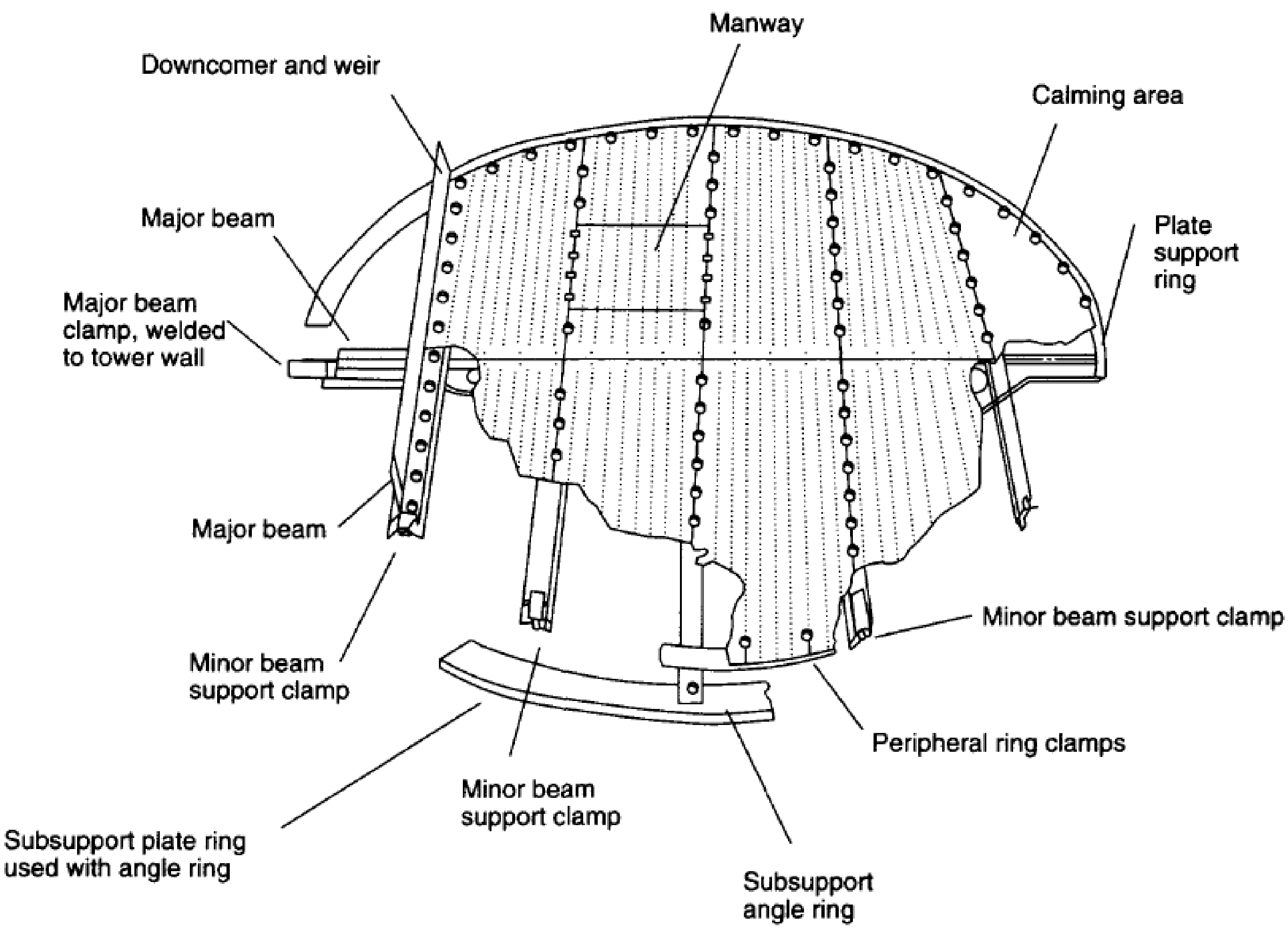
Shown below is a tabulation of the various column specifications along with their values :-

Column Design specification	**Symbol**	**Value**
Height	H	10.1 m
Diameter	d_{col}	0.8 m
Number of trays	N	20 (real)
Tray spacing	-	450 mm
Hole diameter	d_h	4 mm
Plate thickness	t_p	4 mm
Weir height	h_w	40 mm
Top disengaging space	t_d	450 mm
Bottom separation space	B_s	1000 mm
Material of construction	-	IS : 2004 - 1962
Maximum allowable stress	f	100 Mpa

Density of material	ρ_s	7833.4 kg/m3
Material of insulation	-	Asbestos
Thickness of insulation	t_{ins}	50 mm
Density of insulation	ρ_{ins}	270 kg/m3
Skirt height	h_{skirt}	2 m
Operating pressure	-	131325 Pa
Design pressure	p	144456 Pa
Operating temperature	-	87 deg C
Design temperature	temp	95.7 deg C

Plate construction

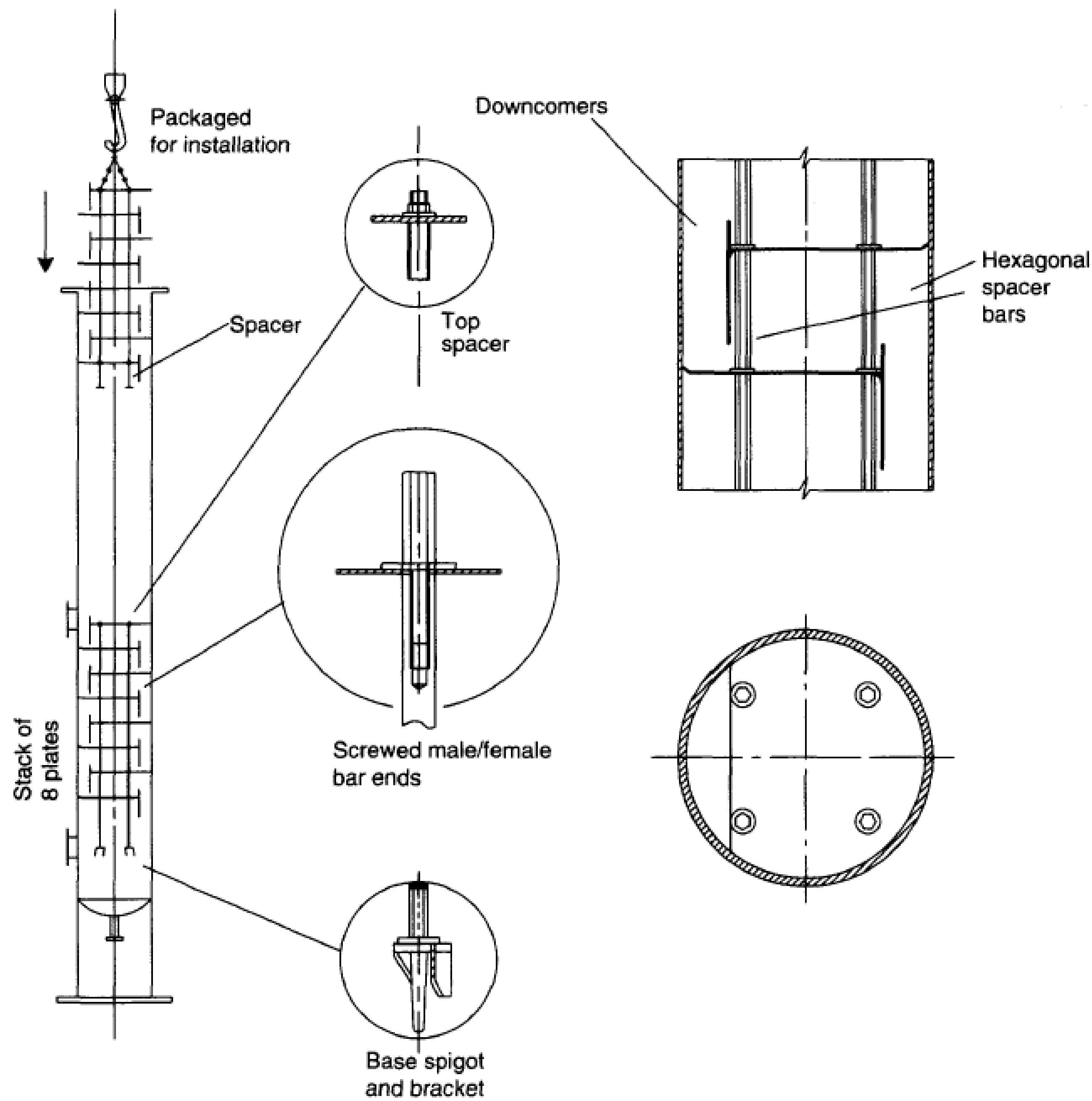
There are basically two types of plate constructions : Sectional and Cartridge type construction.



A typical sectional plate construction

The trays, downcomer segments and other tray components are usually constructed in sections for column diameter of 1 m and above. The plate sections are designed in such that it can be removed through the column manholes, preferably detachable from both above tray and tray below. Support ring width is usually between 40 to 90 mm. Trays are either clamped or bolted to the support ring. Support rings and minor beams for small diameter column are used.

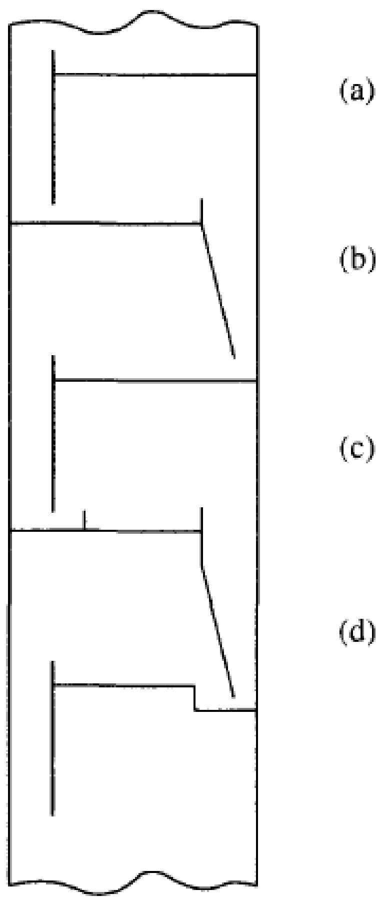
Cartridge or stacked type of construction is done in case of column diameter less than 1m, since in this case the entry of workers to clean and install parts inside the column is not possible. The tall column is divided into numbers of flanged sections and the prefabricated cartridge tray assemblies are installed in each flanged sections with suitable downcomer clearance. The plates are not fixed to the shell wall and leakage may occur.



A typical stacked plate construction

<u>Downcomer details</u>

The segmental downcomer, is the cheapest and the simplest type of construction which is mostly satisfactory in many cases. The downcomer residence time of more than 3 s is desirable to get only clear liquid on the tray. The different types of segmental downcomers constructions are shown -



Segment (chord) downcomer designs. (*a*) Vertical apron (*b*) Inclined apron (*c*) Inlet weir (*d*) Recessed well

Different types of segmental downcomer designs

<u>Minimum thickness of shell</u>

$t_s = \frac{pDi}{2fJ-p}$ = $(144456 * 0.8)/(2 * 1000000 * 0.8 - 144456)$ = 0.722 mm ~ 1 mm

Now, thickness as per calculation is 1 mm but according to recommended shell thickness in IS : 4503-1967, the value is 10 mm hence, we will take 10 mm as the shell thickness.

∴ $t_s = 10$ mm

<u>Head</u>

Standard ellipsoidal head is used having $\frac{major\ axis}{minor\ axis} = 2$

$t_h = \frac{pDi}{2fJ-0.2p} =$ (144456* 0.8)/(2*1000000*0.8 – 0.2*144456) = 0.722 mm ~ 1 mm

Now, as per recommendations of IS : 4503-1967, the thickness of head and shell are kept same for uniformity since the same material is being used for constructing both the parts.

TABLE 4 MINIMUM SHELL THICKNESSES WHERE SEVERE CONDITIONS ARE NOT EXPECTED

(*Clause* 9.3.3.1)

Nominal Diameter mm	Minimum Thickness in mm						
	Cast Iron	Carbon Steel (Including Corrosion Allowance)	Copper and Copper Alloys	Aluminium and Aluminium Alloys	Austenitic Stainless Steel	Nickel	Monel Inconel
150	10	5	3·2	5	3·2	3·2	3·2
200	10	6·3	3·2	5	3·2	3·2	3·2
250	10	6·3	3·2	5	3·2	3·2	3·2
300	13	6·3	3·2	5	3·2	3·2	3·2
350	13	6·3	5	5	3·2	5	3·2
400	13	6·3	5	6·3	3·2	5	3·2
500	13	8	6·3	8	3·2	6·3	3·2
600	16	8	6·3	8	5	6·3	5
700	16	10	8·0	10	5	8	5
800	16	10	10	11·2	6·3	8	6·3
900	19	10	10	11·2	6·3	10	6·3
1 000	19	10	11·2	12·5	6·3	11.2	6·3
1 100	22	11·2	11·2	14	6·3	11·2	6·3

NOTE — The thickness values are exclusive of the corrosion allowance.

Minimum shell thickness as per IS : 4503-1967

12.2 Thickness — Shell covers shall have a thickness at least equal to the thickness of the shell when the same material of construction is used both for the shell and cover.

Shell head/cover recommendations as put forward by IS : 4503-1967

Column Height

H = 450 + (450*19) + (19*4) + 1000 ~ 10.1 m

CALCULATION OF STRESSES

Definition of certain variables used;

Quantity	**Symbol**
Axial stress	f_{as}
Circumferential stress	f_{cs}
Stress due to shell	$f_{\text{dead wt. shell}}$
Stress due to insulation	$f_{\text{dead wt. insulation}}$
Stress due to liquid in the column	$f_{\text{dead wt. liquid}}$
Stress due to column attachments	$f_{\text{dead wt attachments}}$
Total dead load stress	$f_{\text{dead wt. total}}$
Bending stress due to wind above guy	$f_{\text{wind,H, above guy}}$
Bending stress due to wind below guy	$f_{\text{wind,H, below guy}}$
Compressive stress due to guy wire tension	$f_{\text{com. Guy}}$
Seismic stress	f_{sb}

1) Axial and circumferential stresses

$f_{as} = \frac{p * Do}{4 * j * ts}$ = (144456*0.82)/(4*0.8*0.01) = 3.7 MPa

$f_{cs} = 2 * f_{as}$ = 7.4 MPa

2) Compressive stresses by dead loads

Firstly we calculate the mass of the shell,

$m_{shell} = [(\pi/4)*(D_o^2 – D_i^2)H\ \rho_s] * 1.2 = 2411.16$ kg …..20% extra mass of bolts, covers, flanges,etc.

∴ Weight of shell = m_{shell} g = 24111.6 N

$f_{\text{dead wt. shell}} = \frac{mshell*g}{\left(\frac{\pi}{4}\right)(Do2 - Di2)}$ = 24111.6/(0.785*(0.82^2 – 0.8^2)) = 0.93 MPa

Similarly we find, mass of insulation, $m_{ins} = \pi D_{ins}\ \rho_{ins}\ H\ t_{ins} = 394$ kg

$f_{\text{dead wt. insulation}} = \frac{Wins}{\pi Dm(ts-c)}$ = 0.17 MPa …. $D_{ins} \sim D_{mean} = D_o + 2(t_{ins})$

The total liquid present in the column also produces stress, and this depends on the number of trays and the diameter of the column, etc.

Mass of liquid in the column = (active area per tray)*(N)*(Liquid depth on tray)*(Density of liquid)*1.3

…..we took 30 % extra for liquid held in downcomers

……density of liquid will be the maximum liquid density from among both the sections of the column and in our case its 1461 kg/m3

∴ m_{liquid} = 885.5 kg

∴ $f_{\text{dead wt. liquid}} = \frac{Wliq}{\pi Dm(ts-c)}$ = 0.38 MPa

Now we must also incorporate stresses due to attachments and/or accessories like ladders, overhead condenser, platform, etc. so,

Weight of attachments = 100 % of the weight of shell = 2111.6 N

∴ $f_{\text{dead wt attachments}} = \frac{Wattach}{\pi Dm(ts-c)}$ = 1.04 Mpa

Hence, total dead load stress acting along the longitudinal axis of the shell,

$f_{\text{dead wt. total}} = f_{\text{dead wt. shell}} + f_{\text{dead wt. insulation}} + f_{\text{dead wt. liquid}} + f_{\text{dead wt attachments}}$

= 2.52 Mpa

This value is << than the maximum allowable stress for the MoC.

We now move on to calculate the wind loads and the seismic loads.

<u>3) Stresses due to wind</u>

Wind plays a very important role for the designing of the tall vessels like the distillation column. Wind speed or the pressure due to the wind on the vessel depend on the location where the vessel is situated. For example, if the vessel is situated along a coastal or a mountainous city, then it is obvious that the effect of wind will be tremendous.

Similarly, if the site location is situated in flat plains in the interior of the landmass, then the effect of wind will not be very significant. In our case, the site location is in Hyderabad (Telangana) city of India, which is located in the interior of the Indian peninsula.

Wind effect at Hyderabad = 35.8 m/s or 974 Pa (NBC map of India)

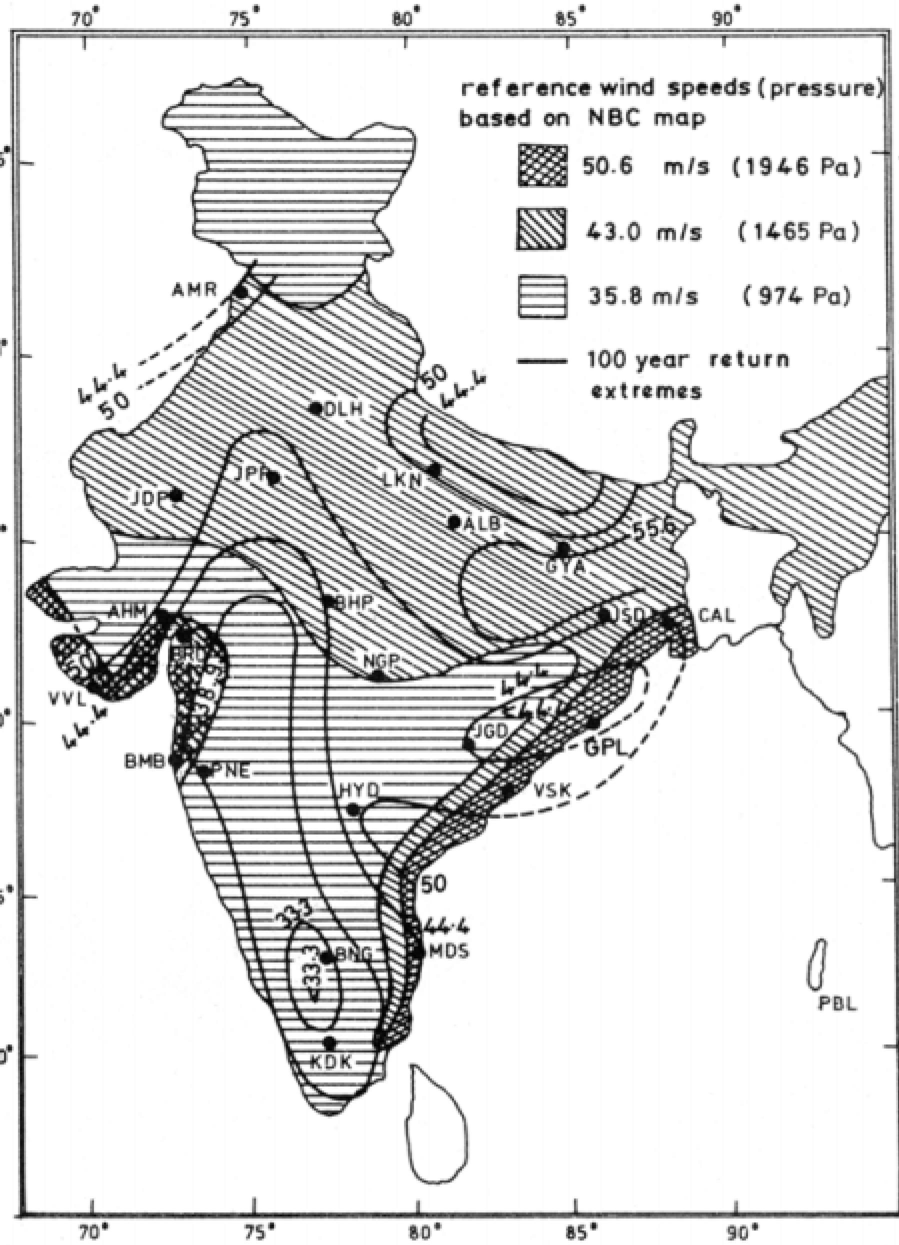
Four guy cables are equally placed for the column subtending an angle of 45 degree with the vertical.

<u>Above guy ring:</u>

Bending moment = Mw = $\left(\frac{1}{2}\right)(PH^2Deff)$ …. Here P = 974 Pa, $D_{eff} = D_{mean}$

$\therefore f_{\text{wind,H, above guy}} = \frac{4Mw}{\pi Dm^2(ts-c)}$ = 8.6 Mpa

Now, for below the guy we find it as,



Reference winds and pressure based on NBC map of India

$f_{wind,H,\ below\ guy} = f_{wind,H,\ above\ guy} / 16$

$= 0.54$ Mpa

Now, the compressive stress induced in the column due the guy wire tension,

$$f_{com.\ Guy} = \frac{0.04 PwHDeff}{\tan(\vartheta) Do(ts-c)}$$

where, P_w = 974 Pa, $D_{eff} = D_{mean}$, tan ϑ = 1 (as ϑ = 45 degree)

∴ The value is, $f_{com.\ Guy}$ = 0.055 Mpa

Now, we finally find the total stress on the upwind side and the downwind side of the column as shown below –

Total stress (Upwind) = $f_{wind,H,\ above\ guy} + f_{cs} - f_{dead\ wt.\ total}$ = 13.48 Mpa

Total stress (Downwind) = $f_{wind,H,\ above\ guy} + f_{as} + f_{com.\ Guy} - f_{dead\ wt.\ total}$ = 9.84 Mpa

∴ The maximum stress due to wind is the one which is maximum among upwind and downwind side.

In this case, it is the Upwind side having the magnitude of 13.48 Mpa. This value is much lesser than the maximum allowable stress for the MoC.

4) Seismic stress

Analysis of seismic effects on the building is of utmost importance. We know that earthquakes are a disastrous natural calamity and it causes huge loss to life and property. Hence, we engineers have to make sure that the vessel which we are planning to erect comfortably withstands the stresses which are developed in the vessel during an earthquake or earthquake-like tremors.

TABLE 2 VALUES OF BASIC SEISMIC COEFFICIENTS AND SEISMIC ZONE FACTORS IN DIFFERENT ZONES

(*Clauses* 3.4.2.1, 3.4.2.3 *and* 3.4.5)

Sl No.	Zone No.	Method: Seismic Coefficient Method — Basic horizontal seismic coefficient, α_0	Method: Response Spectrum Method (*see* Appendix F) — Seismic zone factor for average acceleration spectra to be used with Fig. 2, F_0
(1)	(2)	(3)	(4)
i)	V	0·08	0·40
ii)	IV	0·05	0·25
iii)	III	0·04	0·20
iv)	II	0·02	0·10
v)	I	0·01	0·05

Table showing the value of Basic seismic coefficient

The calculation of seismic stresses involves the use of Indian Standard 1893 (1984) – Criteria for Earthquake-resistant design of structures. This contains the data for the evaluation of the design value of the horizontal seismic coefficient, which is a crucial parameter while dealing with seismic stresses.

It is important for us to understand that the seismic coefficient depends on a lot of variable factors and hence it is very difficult task to exactly find out the value, hence we rely on broad-range methods which can be applied in different zones of the country. Also it is important to know the Zone in which the site location falls under. In this case, Hyderabad in under Zone I (as per map given in IS 1893 (1984)).

We calculate the design value of horizontal seismic coefficient as;

$\alpha_h = \beta \, I \, \alpha_0$ where,

β = parameter for the soil-foundation system

= 1.0 (assumed to be Type I Hard soil with Raft foundation)

I = Importance factor = 1.0

α_0 = Basic value of the seismic coefficient = 0.02

$\therefore \; \alpha_h = 0.02$

$\therefore$ Seismic stress , $f_{sb} = \frac{2\alpha h \, W \, H}{3\pi R^2 t} = 0.938$ MPa

TABLE 3 VALUES OF β FOR DIFFERENT SOIL-FOUNDATION SYSTEMS

(*Clause* 3.4.3)

Sl No.	Type of Soil Mainly Constituting the Foundation	Values of β for					
		Piles Passing Through Any Soil, but Resting on Soil Type I	Piles Not Covered Under Col 3	Raft Foundations	Combined or Isolated RCC Footings with Tie Beams	Isolated RCC Footings Without Tie Beams or Unreinforced Strip Foundations	Well Foundations
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
i)	Type I Rock or hard soils	1·0	—	1·0	1·0	1·0	1·0
ii)	Type II Medium soils	1·0	1·0	1·0	1·0	1·2	1·2
iii)	Type III Soft soils	1·0	1·2	1·0	1·2	1·5	1·5

Note — The value of β for dams shall be taken as 1·0.

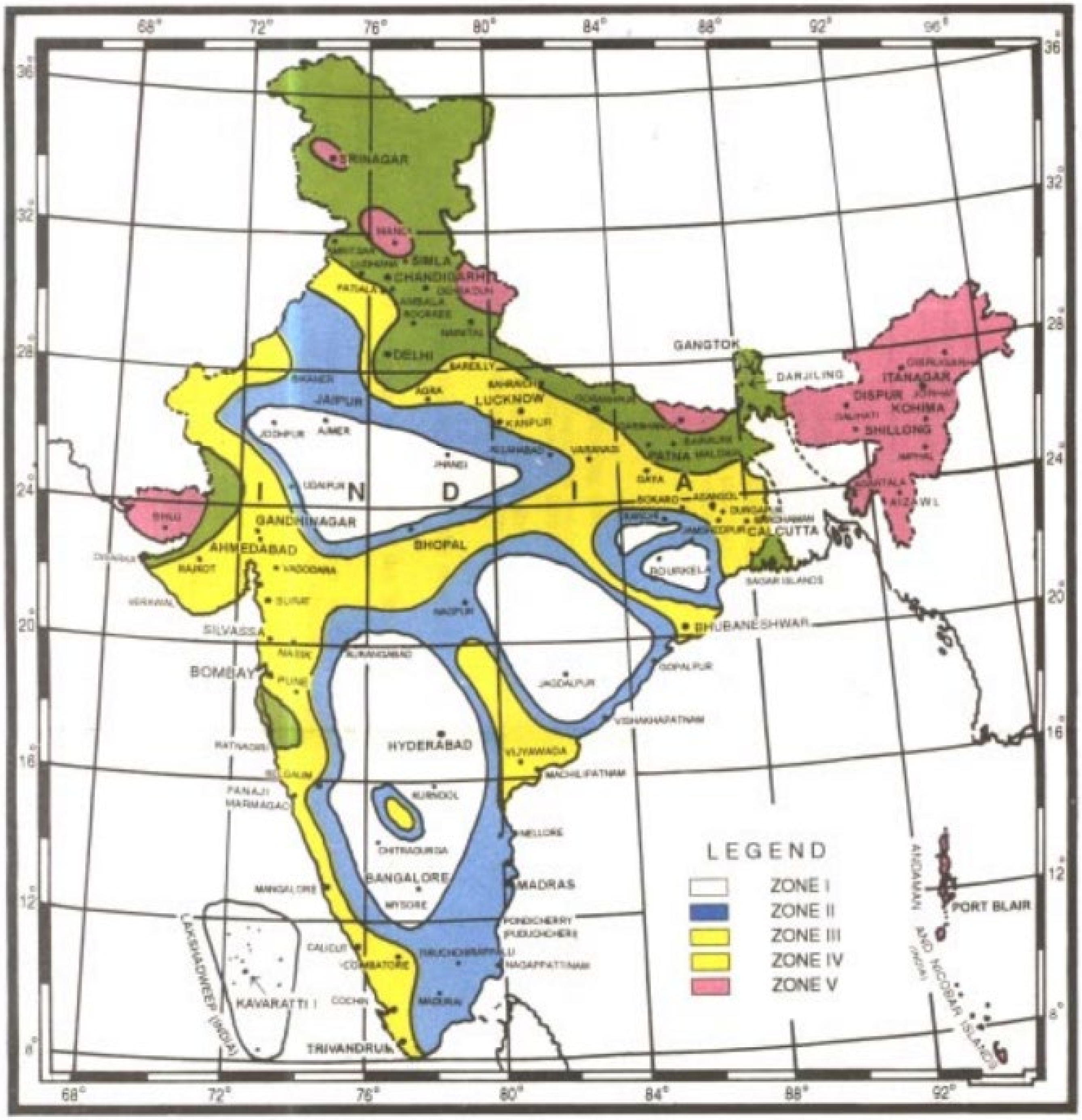
TABLE 4 VALUES OF IMPORTANCE FACTOR, *I*

(*Clauses* 3.4.2.3 *and* 3.4.4)

Sl No.	Structure	Value of Importance Factor, *I* (*see* Note)
(1)	(2)	(3)
i)	Dams (all types)	3·0
ii)	Containers of inflammable or poisonous gases or liquids	2·0
iii)	Important service and community structures, such as hospitals; water towers and tanks; schools; important bridges; important power houses; monumental structures; emergency buildings like telephone exchange and fire bridge; large assembly structures like cinemas, assembly halls and subway stations	1·5
iv)	All others	1·0

Note — The values of importance factor, *I* given in this table are for guidance. A designer may choose suitable values depending on the importance based on economy, strategy and other considerations.

Tables above provide values of β and I



Seismic Zoning map of India

Where,

W = weight of the column

R = Do/2

t = thickness of column

Now, we have all the ingredients to calculate the maximum possible stress which the column would be exposed to, as shown below –

Maximum possible stress = Total stress (Upwind) + Seismic stress = 14.42 Mpa ~ 15 Mpa

This value of 15 Mpa is <<< than the maximum allowable stress (100 Mpa) for the material of construction i.e. IS: 2004- 1962. Hence, we have found satisfactory answers to all our questions which we had posed at the beginning of this section. As per the calculations, we can now be certain that the column can withstand different stresses and remain comfortably safe.

DESIGN OF SUPPORTS

Introduction:

The design of a process vessel cannot be complete without the selection and design of practical support for it and without examining the effect of support on the shell. A process vessel is usually supported either in a vertical or horizontal position depending upon the process requirement. For example, a distillation column, an absorption tower, an evaporator or a stirred tank reactor will always be supported in a vertical position. On the other hand, a heat exchanger or condenser or a storage vessel can. Be supported either in vertical or horizontal position depending upon the floor area and headroom available.

For vertical vessels, the common supports are:

- Skirt support
- Bracket or lug support
- Leg support
- Ring support

For horizontal vessels, the common supports are:

- Saddle support
- Leg support
- Ring support

Since the given process equipment is distillation column which is a vertical equipment therefore the best possible support for this equipment would be skirt support.

Wind and Seismic load calculations:

W_s : Weight of shell = 23.6 kN

W_i : Weight of insulation = 3.531 kN

W_l : Weight of liquid = 8.686 kN

W_a : Weight of attachments = 23.6 kN (100% of shell)

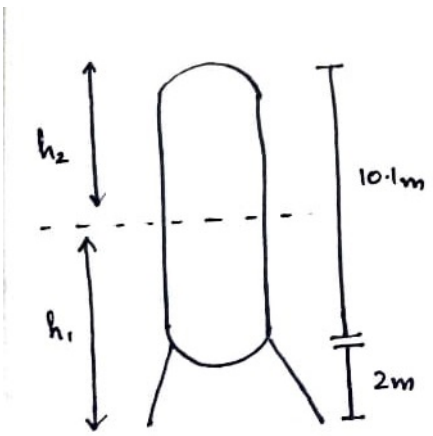
W_t : Total weight of column (max weight) = 59.417 kN

T : Period of oscillation

$$T = 6.35 \times 10^{-5} \left[\frac{H}{D_o - t}\right]^{3/2} \left[\frac{W_t}{t}\right]^{1/2}$$

$$T = 0.3s \Rightarrow T < 0.5.$$

H : Height of column = (10.1 + 2)m = 12.1m



$t_s = 0.01m$

$t_i = 0.05m$

$D_o = 0.8m$

$h_1 = 7.05m$

$h_2 = 5.05m.$

$h_1 = 7.05m$, $h_2 = 5.05m$

$k_1 = 0.7$ (for cylindrical shell), $k_2 = 1$ (since $T < 0.5s$)

Nature of the region	Wind pressure (kN/m^2)	
	H = 20 m	H = 100 m
Coastal area	0.7-1.0	1.5-2.0
Area with moderate wind	0.4	1.0

Table 1: Wind Pressure Relationship

Using the data from Table 1 and interpolation P_1 and P_2 are calculated

$P_1 = 0.838\ kN/m^2$

$P_2 = 0.869\ kN/m^2$

P_{bw} : Force due to wind load acting on bottom part of the vessel

P_{uw} : Force due to wind load acting on bottom part of the vessel

$$P_{bw} = k_1 k_2 \ P_1 \ h_1 \ D_{io} = 0.7 \times 1 \times 0.838 \times 7.05 \times (0.8 + 0.05) \Rightarrow P_{bw} = 3.515\ kN$$

$$P_{uw} = k_1 k_2 \ P_2 \ h_2' \ D_{io} = 0.7 \times 1 \times 0.869 \times 9.575 \times (0.8 + 0.05) \Rightarrow P_{uw} = 4.951\ kN$$

M_w : Bending moment due to wind load = 59.796 kNm

$$M_w = P_w \left(\frac{h_1}{2}\right) + P_{uw} \left[h_1 + \left(\frac{h_2}{2}\right) \right] \Rightarrow M_w = 59.796\ kN.m$$

M_s : Bending moment due to seismic load = 95.850 kNm

$$M_s = \frac{2}{3} C_s W_t H = 95.85 \text{ kN.m}$$

Where C_s can be found using Table 2 below

Seismic zone	Seismic coefficient, C_s		
	$T < 0.4$	$0.4 < T < 1$	$T > 1.0$
Mild	0.05	0.02/T	0.02
Medium	0.1	0.04/T	0.04
Severe	0.2	0.08/T	0.08

Table 2: Seismic Coefficient

Therefore, we have,

$$\tau_{zsm} = \frac{4M_s}{\pi t (D_o - t)^2} = 19.5 \text{ MN/m}^2$$

$$\tau_{zwm} = \frac{4M_w}{\pi (D_i + t)^2 t} = 12.2 \text{ MN/m}^2$$

$\boldsymbol{\sigma_{zp}}$ **:** Due to pressure = 2.77 MPa

$\boldsymbol{\sigma_{zw}}$ **:** Due to dead weight = 2.395 MPa

$\boldsymbol{\sigma_z}$ (tensile) = 19.875 MPa

$\boldsymbol{\sigma_z}$ (compressive) = 19.125 MPa

$\boldsymbol{\sigma_\theta = P(D_o - t)/ 2t}$ = 5.68 MPa

$\boldsymbol{\sigma_z}$ **:** Equivalent stress = $\boldsymbol{(\sigma_\theta - \sigma_\theta \sigma_z + \sigma_z^2 + 3t^2)}$ = 22.658 MPa

Design of Skirt Support:

Skirt supports are cylindrical or conical steel shells attached to the bottom tangent of the vertical vessels. These supports are found to be most suitable for tall vessels subjected to longitudinal bending stresses. The section modulus of the skirt is maximum for a given metal sectional area, as it is concentrated at the maximum distance from the axis of the vessel. Therefore, this type of supports is a very suitable structure for vessels subjected to wind, seismic and other loadings, which cause bending moment at the vessel's base.

The skirts are not subjected to operating pressure conditions as in the case of pressure vessels, and therefore, the selection of material is not limited to the steels permitted by the pressure-vessel codes. The structural steels with corresponding allowable stress may be used for the skirt, and this will be economical.

- **Skirt-wall thickness (t_{sp}):**

The maximum stress will be induced in the skirt due to the action of the dead weight of the vessel and the wind or seismic bending moment, as the skirt is not subjected to internal or external pressure, like the vessel's shell.

The maximum tensile stress in the skirt wall is given by:

$\boldsymbol{\sigma_z}$ **(tensile, max) = ($\boldsymbol{\sigma_{zwm}}$ or $\boldsymbol{\sigma_{zsm}}$) - $\boldsymbol{\sigma_{zw}}$**

The maximum compressive stress in the skirt wall is given by:

$\boldsymbol{\sigma_z}$ **(compressive, max) = ($\boldsymbol{\sigma_{zwm}}$ or $\boldsymbol{\sigma_{zsm}}$) + $\boldsymbol{\sigma_{zw}}$,** where

$\boldsymbol{\sigma_{zw}}$ = the stress due to total dead weight supported by the skirt
$\boldsymbol{\sigma_{zsm}}$ = the stress due to wind moment at the base of the skirt
$\boldsymbol{\sigma_{zwm}}$ = the stress due to seismic bending force

To make sure that the skirt thickness so found does not fail, the following conditions are to be checked:

Case 1: $\boldsymbol{\sigma_z}$ (tensile) ≤ *fJ* cos*α*

$\boldsymbol{W_{min}}$ = 23.6 kN

Thickness Correction factor for without insulation condition = 0.94

Weight Correction factor = 0.39

$\boldsymbol{(\sigma_{zw})_{new} = 9.39/t_{sp}}$

$(P_{bw})_{new}$ = 3.514 * 0.94 = 3.308 kN

$(P_{uw})_{new}$ = 4.951 * 0.94 = 4.659 kN

$(M_w)_{new}$ = 3.308(7.05/2) + 4.659(9.575) = 56.27 kNm

$\boldsymbol{(\sigma_{zwm})_{new} = 112/t_{sp}}$

T_{new} = 0.18 < 0.5 therefore k_2 is till equal to 1

$(M_s)_{new}$ = 95.85 * 0.39 = 38.07 kNm

$(\sigma_{zsm})_{new} = 75.77/t_{sp}$

σ_z (tensile, max) = max of $(\sigma_{zwm}$ or $\sigma_{zsm})_{min} - (\sigma_{zw})_{min}$

$$fJ \cos\alpha = 112/t_{sp} - 9.39/t_{sp}$$

t_{sp} = 1.02 mm

Case 2: σ_z (compressive) ≤ 0.125 E (t/D) cosα

E: Modulus of elasticity = 2 x 10^8 Pa

W_{mzx} = 119.866 kN

Weight Correction factor = 2.01

$(\sigma_{zw})_{new} = 47.71/t_{sp}$

P_{bw} = 3.514 kN

P_{uw} = 4.951 kN

M_w = 59.796 kNm

T_{new} = 0.18 < 0.5 therefore k_2 is till equal to 1

$(M_s)_{new}$ = 95.85 * 2.01 = 193.36 kNm

Since M_s is greater than M_w therefore σ_{zsm} will be greater than σ_{zwm}

$(\sigma_{zsm})_{new} = 384.87/t_{sp}$

σ_z (compression, max) = max of $(\sigma_{zwm}$ or $\sigma_{zsm})_{max} + (\sigma_{zw})_{max}$

$$0.125\ E\ (t_{sp}/D) \cos\alpha = 384.87/t_{sp} - 47.71/t_{sp}$$

t_{sp} = 3.70 mm

The minimum thickness of the skirt wall in corroded condition should not be less than 7 mm as per IS: 2825 — 1969.

Therefore thickness of the skirt wall is 7mm. (i.e. , t_{sp} = 7mm)

- **Design of skirt-bearing-plate:**

The bearing-plate at the base of the skirt is essential to increase the load-bearing contact area with the foundation, which has got low bearing capacity per unit area.

The bearing plate, which is welded to the bottom of the skirt of the vessel, must be securely anchored to the concrete foundation using anchor bolts embedded in the concrete to prevent overturning from the bending moments induced by wind or seismic loads.

The maximum compressive stress between the bearing plate and the concrete foundation is given by:

$$\sigma_c = \frac{W_{max}}{\pi (D_{os} - \ell)\ell} + \frac{M_w / M_s}{\pi \left(\frac{D_{os} - \ell}{2}\right)^2 \ell} \quad ; \quad \begin{array}{l} \ell = 0.1\,m \\ \ell/b = 1 \quad \therefore \quad b = 0.1 \\ \ell : \text{width of bearing plate} \end{array}$$

σ_c = 3465.11 kN/m^2

W_{max} = maximum weight of the vessel

A = area of contact between bearing plate and concrete foundation

M_s = bending moment due to wind load

M_w = bending moment due to seismic load

Z = section modulus of area A

The thickness of the bearing plate is determined by considering it as a uniformly loaded cantilever beam with σ_c (max.) the uniform load. The maximum bending moment for such a beam occurs at the junction of the skirt and the bearing plate and is determined for unit circumferential width (i.e. b) by the following equations:

t_{bp} : thickness of bearing plate

$$t_{bp} = l\sqrt{\frac{3\sigma_c}{f}} = 0.1\sqrt{\frac{3 \times 3465.11}{100 \times 1000}}$$

$$t_{bp} = 32.2\ mm.$$

Thickness of bearing plate is greater than 20 mm therefore gusset plates are required

- **Design of Gusset plates:**

Gussets are used to stiffen the bearing plates and to reduce the net load on bearing plate

t_{gp} : Recalculated bearing plate thickness

$$t_{gp} = \sqrt{\frac{6\,M(max)}{f}}$$

$$t_{gp} = \sqrt{\frac{6 \times 4.123}{10^5}}$$

$$t_{gp} = 15.\ mm.$$

M(max) can be calculate using the data from Table 3. Since l/b = 1 we have,

$M_x = 0.0972\ \sigma_c\ b^2$

$M_y = -0.119\ \sigma_c\ l^2$, absolute value of M_x is less than M_y

So, $M_y = M(max) = 4.123$ kNm

l/b	$M_x \begin{pmatrix} x = b/2 \\ y = l \end{pmatrix}$	$M_y \begin{pmatrix} x = b/2 \\ y = o \end{pmatrix}$
0	0	$-0.500\ \sigma_c\ l^2$
1/3	$0.007\ 8\ \sigma_c\ b^2$	$-0.428\ \sigma_c\ l^2$
1/2	$0.029\ 3\ \sigma_c\ b^2$	$-0.319\ \sigma_c\ l^2$
2/3	$0.055\ 8\ \sigma_c\ b^2$	$-0.227\ \sigma_c\ l^2$
1	$0.097\ 2\ \sigma_c\ b^2$	$-0.119\ \sigma_c\ l^2$
3/2	$0.123\ \sigma_c\ b^2$	$-0.124\ \sigma_c\ l^2$
2	$0.131\ \sigma_c\ b^2$	$-0.125\ \sigma_c$
3	$0.133\ \sigma_c\ b^2$	$-0.125\ \sigma_c$

b = gusset spacing (x direction),
l = bearing-plate outside radius minus skirt outside radius (y direction),
M_x = maximum bending moment at the outer edge mid point caused by deflection of the plane in the x-direction,
M_y = maximum bending moment at the junction of the skirt and bearing-plate caused by deflection of the plane in the y-direction.

Table 3 : Maximum Bending Moments in a Bearing Plate with Gussets

This gives the new recalculate thickness of bearing plate as 15 mm.

Number of gussets = $\pi D_{os}/b$ = 31.5

D_{os} = 0.8 + 0.1*2 = 1m

Required number of gussets plate is 32.

- **Design of Anchor bolts:**

Anchor-bolts prevent the overturning of the vessel from the action of wind or seismic forces, and therefore, they are subjected to tensile stresses only. The requirement of anchor bolts is determined by the stability of the tall vertical vessel. The minimum stress between the bearing plate and the concrete foundation will be,

$$\sigma_{min} = \frac{W_{min}}{A} - \frac{[M_w/M_s]_{\text{max of max}}}{Z}$$

$$= \frac{23.6}{A} - \frac{193.36}{Z}$$

σ_{min} = - 2957.38 kPa

As σ_{min} is negative, the vessel must be anchored to the concrete foundation through anchor bolts to prevent overturning due to the bending moment induced by the wind or seismic load.

Number of anchor bolts required can be calculated as:

$$nP_{bolt} = |\sigma_{min}| A \qquad A: 0.2826\ m^2$$

$$nP_{bolt} = (2957.38)(0.2826) \qquad Z = 0.0635\ m^2$$

$$nP_{bolt} = 835.76\ kN$$

$$nP_{bolt} = (\underbrace{a_r}_{\text{Root area}}\ \underbrace{n}_{\text{no. of bolts}})\ \overset{\text{Allowable stress}}{f_b}$$

$$a_r = 63\ mm^2$$

$$f_b = 57.3\ MPa$$

n = 231.5 bolts

Number of Anchor Bolts required = 232

Thus, the Mechanical designing of the distillation column has been completed successfully.

SIMULATION OF DISTILLATION COLUMN USING DWSIM

The distillation column has been simulated using DWSIM Software. DWSIM is a free and open-source Chemical Process simulator used to simulate a wide variety of process and unit operations involved in Chemical Engineering. When we simulate the distillation column, we are basically using computers to solve the distillation column’s heat and mass balance equations for us. There are various methods/approaches to solve these equations and each one of them has its own pros/cons.

The steps involved in DWSIM for simulating the distillation are as follows :-

- Create a new Process simulation model
- The simulation configuration wizard opens up for us to specify : Compounds, Property packages, and the system of units to used in the simulation.
- Create the flowsheet by drag and dropping the material/energy streams and the distillation column(either shortcut or rigorous distillation model)
- Enter the specifications of the Feed stream, rename the Distillate and the Bottoms stream as preferred

- Enter the detailed specifications for the column, like number of stages (this may be obtained from the results of the shortcut distillation simulation), Condenser and reboiler pressure, interpolating the pressure among all the intermediate stages, connecting the different streams to the column, entering the feed, distillate and bottoms stage, etc.
- Then we can solve the flowsheet to see the results, both in tabulated form as well as reports.
- We may also run Sensitivity analysis in Optimization menu of DWSIM to see how different parameters are related with each other.

In our simulation, we have used Raoult's Law as the property package and have performed Shortcut distillation first and then performed the Rigorous distillation of the column.

Shortcut distillation uses several assumptions like the Constant Molar Overflow assumption, among others, to provide us with the solutions. Thus, the results are not accurate but it provides us a rough estimate of the number of trays, minimum reflux ratio, etc. we would require for the desired separation. It also provides us the flowrates of the liquid and vapor in both the sections of the column, which is really useful.

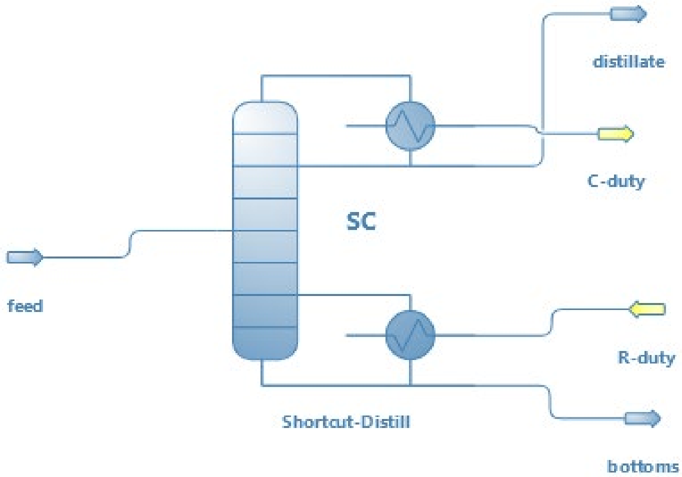
Rigorous distillation, as the name suggests, does a rigorous and complete calculation of the distillation column. It gives us the condenser and reboiler duties, the temperature and pressure for every tray in the column, etc. Thus, it is evident that by performing a rigorous calculation for the column, we can obtain very accurate results.

We have hence found that the liquid and vapor flowrates which have been hand-calculated and the values which have been obtained via simulation are very nearly equal to each other.

Simulation results, graphs and analysis

Following are the details for Shortcut distillation column :-

1) Flowsheet



2) Results

Results

Property	Value	Units
Minimum Reflux Ratio	0.819557	
Minimum Number of Stages	7.67516	
Actual Number of Stages	11.9508	
Optimal Feed Stage	7.5876	
Stripping Liquid	76.9385	kmol/h
Rectify Liquid	49.4501	kmol/h
Stripping Vapor	64.5432	kmol/h
Rectify Vapor	76.3251	kmol/h
Condenser Duty	572.437	kW

3) Analysis

The table shown next will help us in understanding the different parameters –

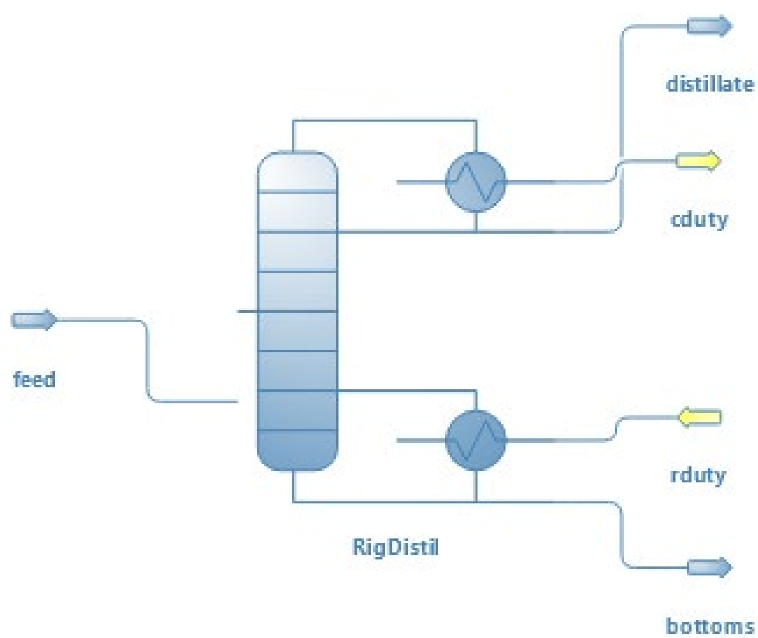
Property	Calculated value	Simulated value	Unit

Minimum reflux ratio	0.92	0.819557	-
Number of trays (ideal)	12.5	11.9508	-
Feed stage	6	7.5876	-
Stripping liquid	76.733	76.9385	Kmol/h
Stripping vapor	64.943	64.5432	Kmol/h
Rectifying liquid	49.715	49.4501	Kmol/h
Rectifying vapor	77.225	76.3251	Kmol/h

So, from the above table we can see that the flowrates match very closely since they are obtained from simple mass balance (overall as well as component-wise mass balance). The number of stages and the minimum reflux ratio is also nearly equal. Thus, the values have been verified by Shortcut distillation column simulation and now we can proceed towards Rigorous simulation.

Following are the details for Rigorous distillation column :-

1) Flowsheet



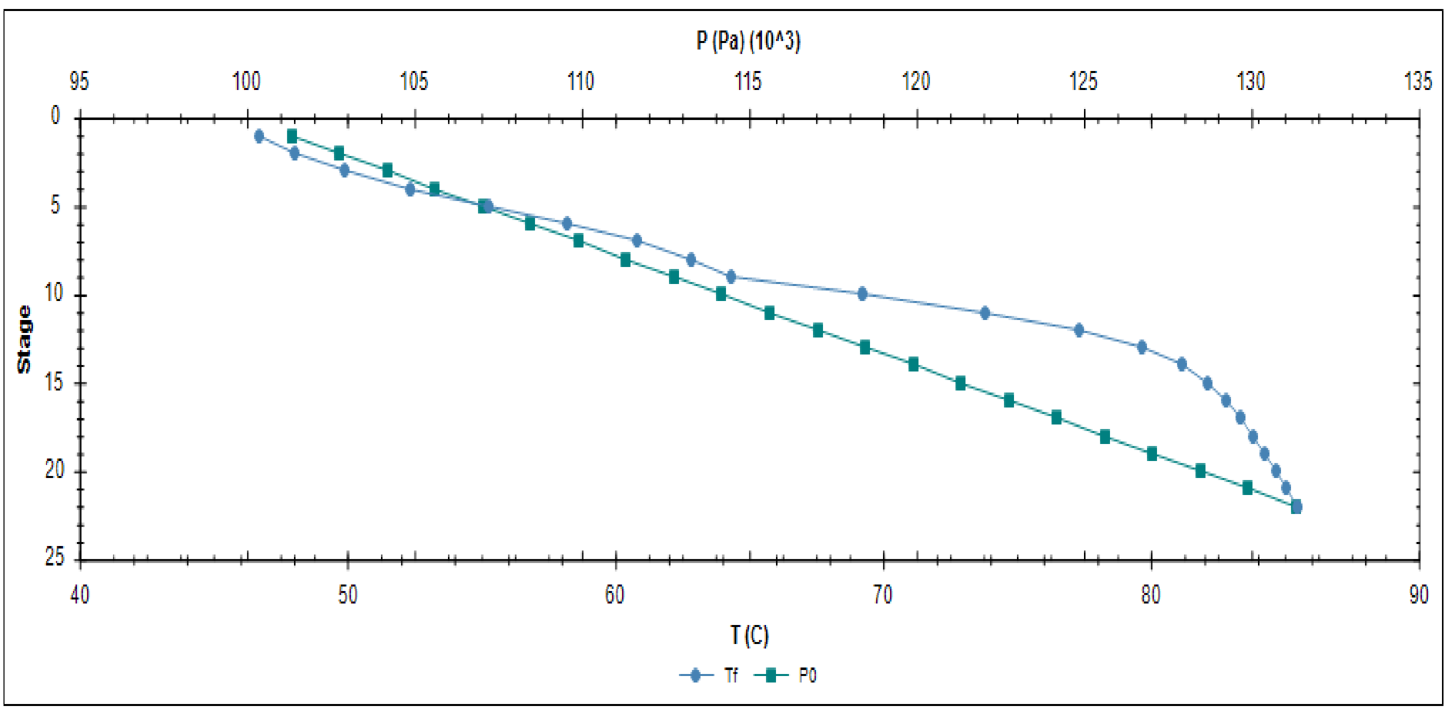
2) Results

Property	Value	
Condenser Pressure	101325	Pa
Reboiler Pressure	131325	Pa
Condenser Pressure Drop	0	Pa
Reflux Ratio	1.84	
Distillate Molar Flow	26.9891	kmol/h
Condenser Duty	575.359	kW
Reboiler Duty	-495.608	kW
Number of Stages	22	

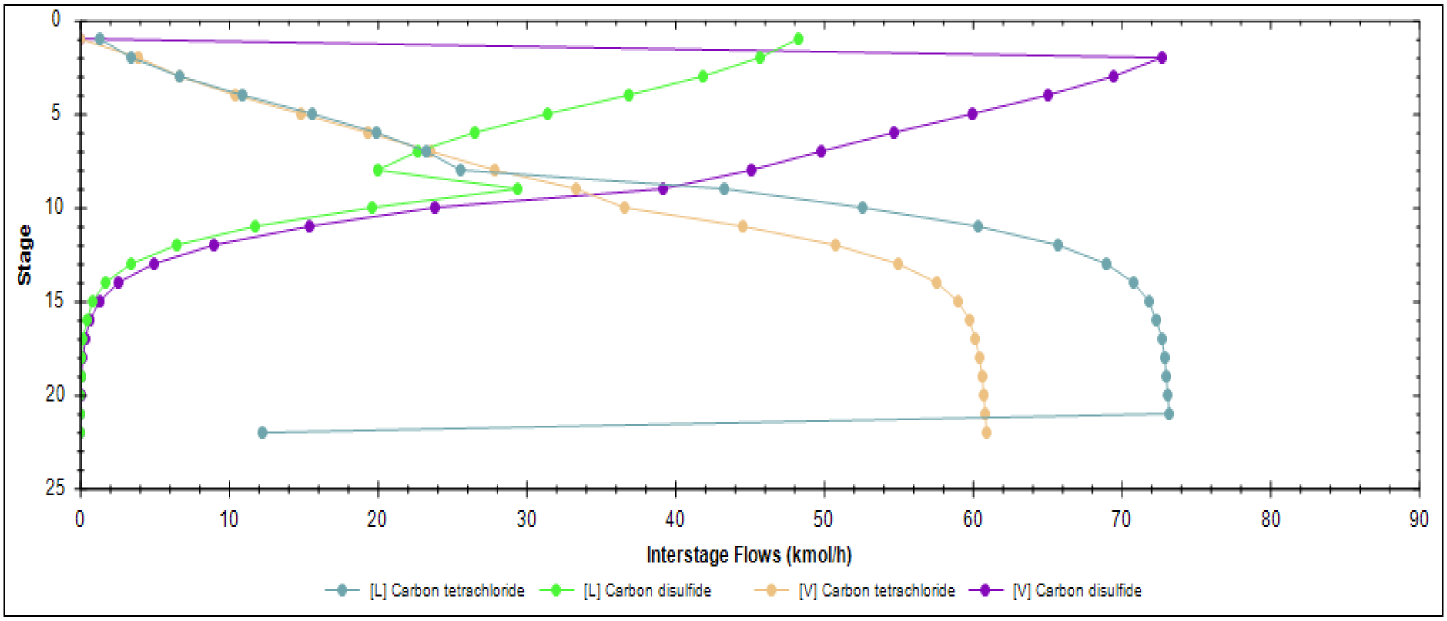
3) Graphs

Shown below are the different graphs obtained after rigorous simulation of the distillation column-

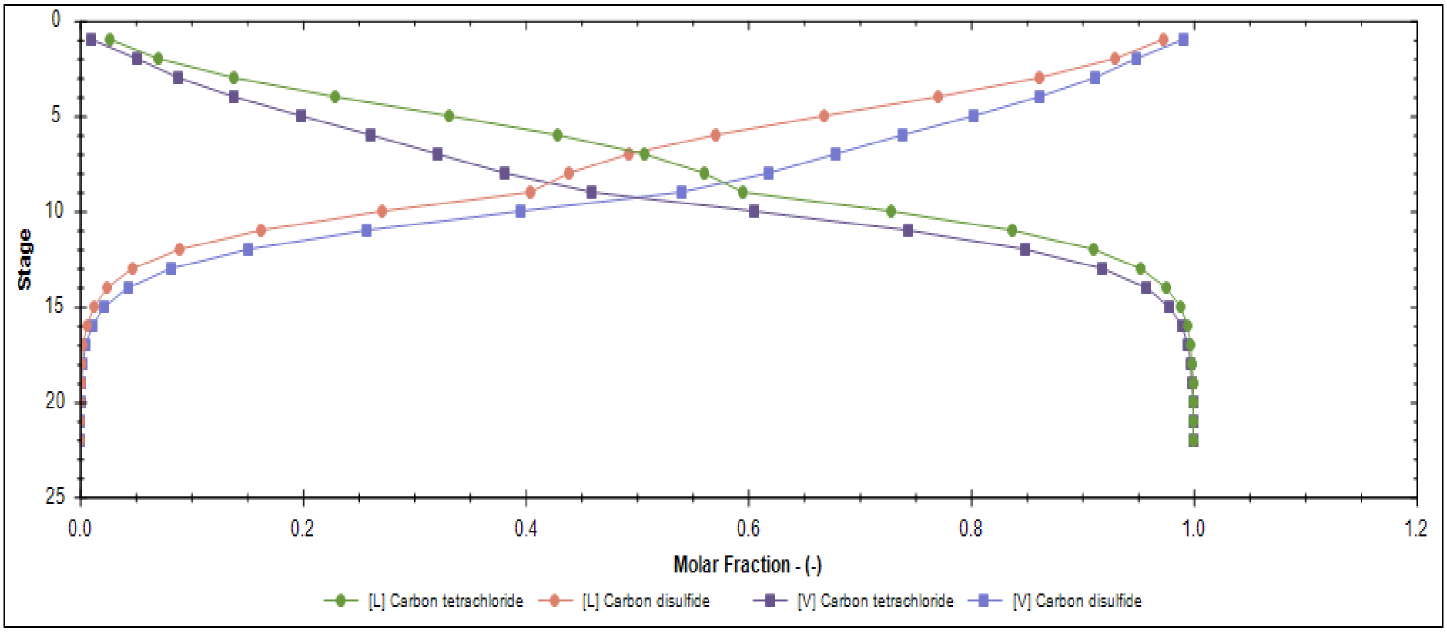
T and P vs Stages



Component flows vs Stages



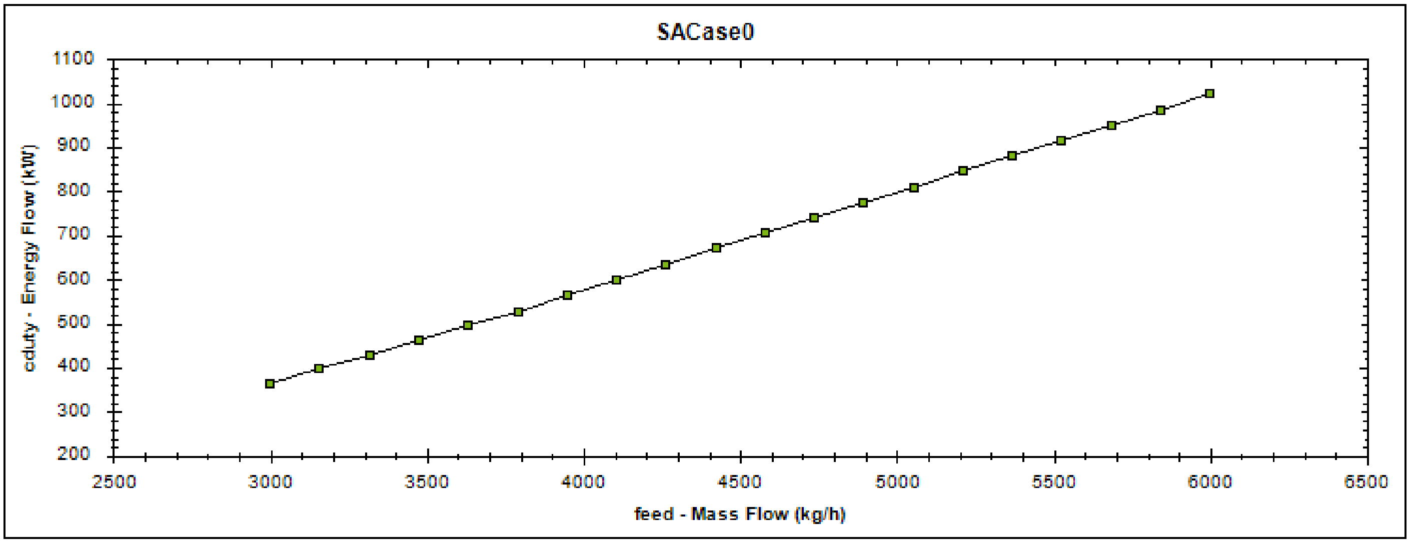
Component mole fractions vs Stages

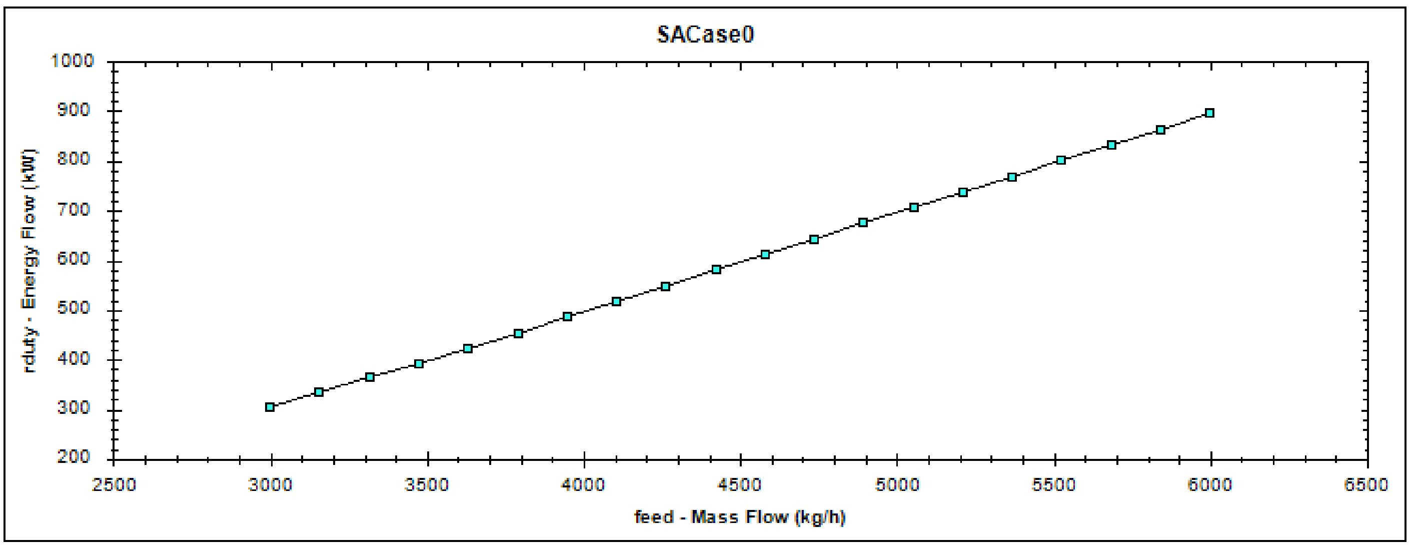


4) Sensitivity analysis

Sensitivity analysis helps us to understand, via case study, the effect of one or more independent variables on one or more other dependent variables. This is particularly useful if one wants to know the relationship between two parameters involved in the simulation. Shown below are a two case studies-

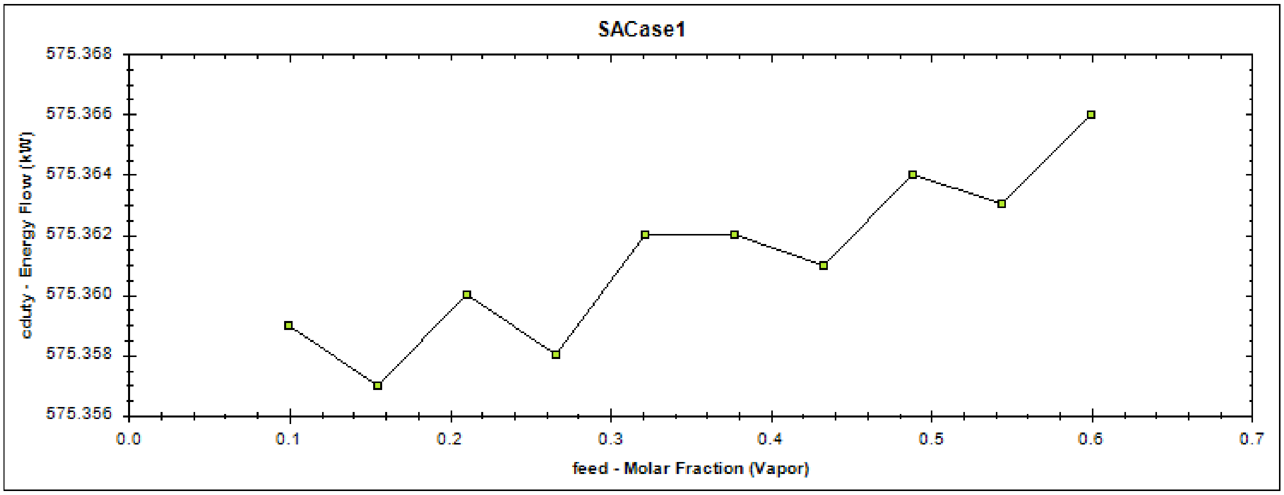
a) Effect of Feed mass flow on Condenser and Reboiler duty

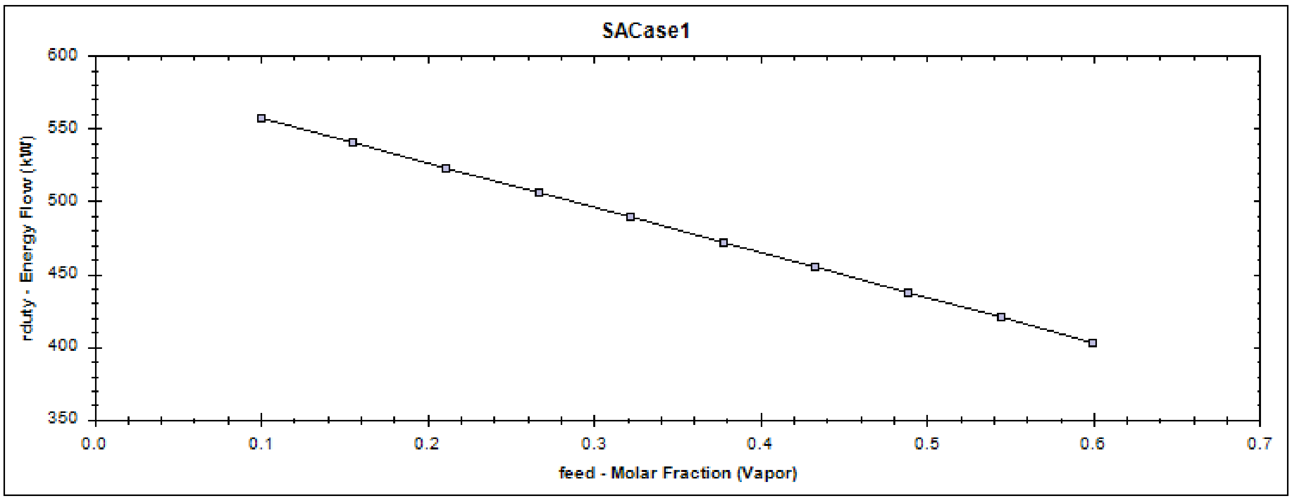




Here we can see that upon increasing the feed mass flowrate, both the condenser as well as the reboiler heat duties are increasing

b) Effect of Molar fraction of vapor in the Feed on Condenser and Reboiler duty





Here we can see that upon increasing the mole fraction of vapor in the feed, we see somewhat opposite trends for the reboiler and the condenser duties. Reboiler duty decreases with the increase in mole fraction of vapor in the feed, whereas the condenser duty, on an average, increases. This is very interesting analysis which is brought forward by these graphs.

5) Results data table

Table

	T0 (C)	Tf (C)
Condenser	53.502	46.718
Stage1	54.204	48.038
Stage2	54.906	49.89
Stage3	55.608	52.347
Stage4	56.31	55.25
Stage5	57.012	58.211
Stage6	57.713	60.818
Stage7	58.415	62.86
Stage8	59.117	64.343
Stage9	59.819	69.244
Stage10	60.521	73.814
Stage_11	61.223	77.303
Stage_12	61.924	79.64
Stage_13	62.626	81.135
Stage_14	63.328	82.114
Stage_15	64.03	82.81
Stage_16	64.732	83.357
Stage_17	65.433	83.827
Stage_18	66.135	84.255
Stage_19	66.837	84.661
Stage_20	67.539	85.056
Reboiler	68.241	85.441

(A)

Table

	[V] Carbon tetrachloride (kmol/h)	[V] Carbon disulfide (kmol/h)	[L] Carbon tetrachloride (kmol/h)	[L] Carbon disulfide (kmol/h)	[Kval] Carbon tetrachloride	[Kval] Carbon disulfide
Condenser	3.49604E-12	3.56504E-10	1.32448	48.3357	0.364096	1.01737
Stage1	3.9363	72.7127	3.47926	45.728	0.377173	1.0473
Stage2	6.73431	69.4622	6.71895	41.8498	0.39833	1.09649
Stage3	10.4486	65.1093	10.9549	36.852	0.429626	1.16947
Stage4	14.8122	59.9839	15.6258	31.4363	0.470079	1.26329
Stage5	19.3238	54.7275	19.9365	26.5219	0.514353	1.36495
Stage6	23.597	49.8506	23.3127	22.6939	0.554992	1.45706
Stage7	27.8356	45.1602	25.5793	20.0133	0.586794	1.52802
Stage8	33.3502	39.2316	43.331	29.4542	0.60861	1.57564
Stage9	36.6174	23.8878	52.5999	19.633	0.704685	1.79096
Stage10	44.5578	15.3952	60.3627	11.755	0.803453	2.00902
Stage_11	50.8173	9.02055	65.7471	6.50446	0.883001	2.18196
Stage_12	55.0415	4.93021	69.0168	3.42354	0.93569	2.29453
Stage_13	57.5825	2.57782	70.8527	1.75136	0.96637	2.35846
Stage_14	59.0101	1.31396	71.849	0.882539	0.982833	2.39125
Stage_15	59.791	0.660543	72.3925	0.441306	0.991335	2.4067
Stage_16	60.2243	0.329513	72.7015	0.219736	0.995653	2.41309
Stage_17	60.4778	0.163499	72.8917	0.109049	0.99782	2.41485
Stage_18	60.6401	0.0807016	73.0221	0.0538697	0.998895	2.41428
Stage_19	60.7564	0.0396906	73.1216	0.0263761	0.999395	2.41251
Stage_20	60.8478	0.0199115	73.2066	0.0126744	0.999697	2.41035
Reboiler	60.9277	0.0116957	12.279	0.000978744	0.999812	2.40783

(B)

Table

	[V] Carbon tetrachloride (-)	[V] Carbon disulfide (-)	[L] Carbon tetrachloride (-)	[L] Carbon disulfide (-)
Condenser	0.00971121	0.990289	0.0266708	0.973329
Stage1	0.0513549	0.948645	0.0707062	0.929294
Stage2	0.0883808	0.911619	0.138339	0.861661
Stage3	0.138286	0.861714	0.229148	0.770852
Stage4	0.198035	0.801965	0.332025	0.667975
Stage5	0.260952	0.739048	0.429125	0.570875
Stage6	0.321276	0.678724	0.506725	0.493275
Stage7	0.381332	0.618668	0.561041	0.438959
Stage8	0.459484	0.540516	0.595327	0.404673
Stage9	0.605195	0.394805	0.728198	0.271802
Stage10	0.743212	0.256788	0.837003	0.162997
Stage_11	0.84925	0.15075	0.909975	0.0900252
Stage_12	0.917791	0.082209	0.95274	0.0472601
Stage_13	0.957151	0.0428492	0.975878	0.0241221
Stage_14	0.978218	0.0217816	0.987866	0.0121342
Stage_15	0.989073	0.0109268	0.993941	0.00605908
Stage_16	0.994558	0.00544166	0.996987	0.00301334
Stage_17	0.997304	0.00269616	0.998506	0.00149381
Stage_18	0.998671	0.00132906	0.999263	0.000737173
Stage_19	0.999347	0.000652847	0.999639	0.000360586
Stage_20	0.999673	0.000327127	0.999827	0.000173102
Reboiler	0.999808	0.000191924	0.99992	7.97023E-05

(C)

Where,

(A) – Table of temperature of various stages, corresponding to graph of T and P vs Stages

(B) – Table of flowrates of different components on different stages, corresponding to graph of Component flows vs Stages

(C) – Table of Mole fraction of different components on different stages, corresponding to graph of

Component mole fractions vs Stages

In this way, simulating the distillation column using a software like DWSIM helps us to get greater insights into our problem and also reinforces our hand-calculations. Simulation also provides the very useful option of doing Sensitivity analysis, wherein we may explore “what-if” questions and investigate the relationship between different parameters and variables involved in the simulation, which may-a-times reveals surprising new connections!

Thus, simulation of the distillation column was completed successfully.

COST COMPUTATION OF THE DISTILLATION COLUMN

In the industry, economics plays a very crucial role. Every process and operation has to be economically sustainable for the industry to generate net profits from their enterprise. Thus, we have to deal with efficient processes whose parameters have been optimized to provide the least possible cost to the company and maximum profits. We hereby calculate the total cost required to operate the distillation column as follows –

The different components of the total cost include –

- Energy Cost : The cost required to supply steam at the reboiler.
- Fixed Cost : The cost required to set up the column and all the associated parts like insulation, supports, etc.

$\therefore$ Total cost = (Energy cost C_1) +(depreciation + interest + maintenance)x(Fixed cost C_2)

All the variables used have been tabulated below –

Variable	Value	Unit	Symbol
Reboiler duty	496	kW	Qr
Cost of steam	1.52	₹/kg	Cs

No. of working days	330	-	N
Latent heat of steam	2257	kJ/kg	λst
No. of stages	20	-	Nst
HETP of column	0.505	-	-
Diameter of column	0.8	m	d_{col}
Radius of column	0.4	m	r_{col}
Density of steel	7833.4	kg/m^3	P_{ins}
Thickness of shell	10	mm	ts
Thickness of head	10	mm	th
Cost of steel	50	₹/kg	C_{steel}
Thickness of insulation	50	mm	t_{ins}
Cost of insulation	2670	₹/kg	C_{asb}
Height of column	10.1	m	H
Thickness of plate	4	mm	t_p
Cross sectional area of column	0.5024	m^2	A_T
Outer diameter of column	0.82	m	D_o
Insulation/ Mean diameter	0.92	m	D_{ins}

Energy Cost, $C_1 = \frac{Qr*Cs*N*24}{\lambda st}$

Fixed cost is calculated by finding out the amount of steel and asbestos we would require to build the column. Then, using the cost of steel and asbestos per kg, we can evaluate the total fixed cost.

Fixed Cost = (Amount of steel needed in kg, M)x(Cost of steel per kg, C_{steel}) +

(Amount of asbestos needed in kg, A)x(Cost of asbestos per kg, C_{asb})

M = [Weir + Downcomer + Nuts, bolts + Trays](N_{stages}) + 2(Head) + Shell +

Attachments/Accessories + Support

Now, Weir = (40 mm)($t_p d_{col}$)

Downcomer = (300mm)($t_p d_{col}$)

Nuts, Bolts = 10 % of Downcomer

$\text{Trays} = ATtp$

$\text{Head} = 2\pi r_{col}^2 t_h$

$\text{Shell} = (\pi/4)(D_o^2 - D_i^2)H\ (1.2)$ ... 20 % extra for its nuts and bolts

Attachments/Accessories = 100 % of shell

Supports = 10 % of total steel required for all other components

Value of rate of depreciation + interest + maintenance = 35 % = 0.35

$A = (\pi/4)(D_{ins}^2 - D_o^2)HP_{ins}$

Therefore, the total cost is given by –

$$T = C1 + 0.35C2$$

$$= 9524043.88 + 0.35(\ MC_{steel} + AC_{asb})$$

$$= 9524043.88 + 0.35(\ (6036)(50) + (442)(2670)\ )$$

$$T = ₹\ 1{,}00{,}42{,}722.88$$

Hence,

Total annual cost to the company for operating the distillation column is :- **₹ 1,00,42,722.88**

In words - One crore forty-two thousand seven hundred and twenty-two rupees and eighty- eight paise

ARTIFICIAL NEURAL NETWORK BASED PRICE MODELLING

Introduction

Artificial neural networks (ANNs), usually simply called neural networks (NNs), are computing systems vaguely inspired by the biological neural networks that constitute animal brains. ANNs began as an attempt to exploit the architecture of the human brain to perform tasks that conventional algorithms had little success with. ANNs are composed of artificial neurons which are conceptually derived from biological neurons. Each artificial neuron has inputs and produces a single output which can be sent to multiple other neurons. The network consists of connections, each connection providing the output of one neuron as an input to another neuron. Each connection is assigned a weight that represents its relative importance. A given neuron can have multiple input and output connections.

Learning Methodology

Supervised learning uses a set of paired inputs and desired outputs. The learning task is to produce the desired output for each input. In this case the cost function is related to eliminating incorrect deductions. A commonly used cost is the mean-squared error, which tries to minimize the average squared error between the network's output and the desired output. Tasks suited for supervised learning are pattern recognition (also known as classification) and regression (function approximation) . This can be thought of as learning with a ”teacher”, in the form of a function that provides continuous feedback on the quality of solutions obtained thus far

Project specification details

In this implementation, the ANN tries to predict the price of the column given certain information about it. This comes with various perks namely-

- Lots of parameters are taken into account before making the final predic- tion
- Dynamic and flexible enough to respond to changes in the parameters and output accordingly
- Simple model architecture based on artificial neural network
- Used logarithmic mean squared error as the loss function to devise the optimization problem

The following pages will lead you through code that does all of these magic.

Data Generator

```python
import numpy as np
import csv

num = 30000

Headings = np.array(["No. of stages", "Reflux ratio", "Feed
     location", "Reboiler Duty(KW)", "HETP(m)", "Thickness of
     material(m)", "No of working days", "Diameter of column(m)", "
     Height of column(m)", "Thickness of shell(m)", "Thickness of
     insulation(m)","Thickness of plate(m)","Total Cost(Rs)" ])
N = np.random.randint(10,31,size=num)
R = np.array([np.round(x,2) for x in np.random.uniform(0.1,4.1,size
     =num)])
FL = np.array([np.random.randint(x//3,x-x//3) for x in N])
Q_r = np.random.randint(100,1001,size=num)
HETP = np.array([np.round(x,2) for x in np.random.uniform(0.2,0.91,
     size=num)])
W_mat = np.random.randint(1,21,size=num)/1000
N_d = np.random.randint(320,341,size=num)
d_col = np.array([np.round(x,2) for x in np.random.uniform(0.3,2.6,
     size=num)])
h_col = np.random.randint(9,16,size=num)
t_s = np.random.randint(8,15,size=num)/1000
t_i = np.random.randint(40,61,size=num)/1000
t_p = np.random.randint(3,7,size=num)/1000


rho_mat = 7833.4
C_s = 50
C_ins = 2670
lambda_steam = 2257
rho_ins = 2400

C_T = []
for i in range(num):
  D_o = d_col[i] + 2*t_s[i]
  D_i = d_col[i]
  D_ins = D_o + 2*t_i[i]
  M = ((0.04*t_p[i]*d_col[i] + ((3.14/4)*d_col[i]**2)*t_p[i] +
     1.1*0.3*t_p[i]*d_col[i]) * N[i] + 4*3.14*((d_col[i]/2)**2)*t_s[
     i]
     + (3.14/4)*(D_o**2 - D_i**2)*h_col[i]*2.4 )* 1.1*rho_mat
  A = 3.14/4*(D_ins**2 - D_o**2)*h_col[i]*rho_ins
  c_t = (Q_r[i]*C_s*N_d[i]*24)/lambda_steam + M*C_s + A*C_ins
  C_T.append(round(c_t,2))

Matrix = []
Matrix.append(N)
Matrix.append(R)
Matrix.append(FL)
Matrix.append(Q_r)
Matrix.append(HETP)
Matrix.append(W_mat)
Matrix.append(N_d)
Matrix.append(d_col)
```

```python
Matrix.append(h_col)
Matrix.append(t_s)
Matrix.append(t_i)
Matrix.append(t_p)
Matrix.append(C_T)


with open("data_test.csv","w") as data:
  data_writer = csv.writer(data, delimiter=",")

  data_writer.writerow(Headings)
  for j in range(num):

    row = [Matrix[i][j] for i in range(13)]
    data_writer.writerow(row)
```

ANN model

```
import pandas as pd
import numpy as np
from sklearn.model_selection import train_test_split
from sklearn.preprocessing import StandardScaler
from tensorflow.keras.models import Sequential
from tensorflow.keras.layers import Dense


df = pd.read_csv('data.csv')
dataset = df.values
X = dataset[:,0:-1]
Y = dataset[:,-1]

X_train, X_test, Y_train, Y_test = train_test_split(X, Y, test_size
    =0.2, random_state=101)


s_scaler = StandardScaler()
X_train = s_scaler.fit_transform(X_train.astype(np.float))
X_test = s_scaler.transform(X_test.astype(np.float))

model = Sequential([
    Dense(12, activation='relu', input_shape=(12,)),
    Dense(32, activation='relu'),
    Dense(1, activation='sigmoid'),
])

model.compile(loss='mean_squared_logarithmic_error', optimizer='
    adam')


hist = model.fit(X_train, Y_train,
          batch_size=32, epochs=10,
          validation_data=(X_test, Y_test))
```

Cost Optimization using Genetic Algorithm

The objective function used in this study is representative of the total annual cost (C) that is made-up of two components, namely, the operating cost (C_1) and the fixed cost (C_2). While C_1 accounts for the energy cost pertaining to the reflux ratio and reboiler duty, the cost component C_2 accounts for the number of stages. The overall optimization objective is expressed as:

Minimize C(x); xkL<=xk<=xkU

Where C (Rs.) is a function of K-dimensional decision variable vector, x = Transpose([x_1, x_2, x_3,…………..x_8]) and xkL and xkU respectively refer to the lower and upper bounds on xk. The python code is given in the below figure:

```
import numpy as np
from numpy import matlib
import matplotlib.pyplot as plt
import random as random
import math

# problem definition
def totalCost(individual):
    # constant                     unit
    costSteam = 1.47              # Rs/kg
    latentheatSteam = 2257        # kJ/kg
    densitySteel = 7833.4         # kg/m^3
    densityAsbestos = 270         # kg/m^3
    costSteel = 50                # Rs/kg
    costInsulation = 2670         # Rs/kg

    #==================================================Genotype and Phenotype=========================#
    # | reboilerDuty | workingDays | stages | columnDia | columnHt | shellTh | insulationTh | plateTh | #
    #                                                                                                 #
    # | 470 to 530 | 325 to 335 | 13 to 25 | 0.3 to 2.5 | 9 to 15 | 8 to 14 | 45 to 55 | 3 to 6 |      #
    #=================================================================================================#

    # independent variable          unit
    reboilerDuty = individual[0] # kW
    workingDays = individual[1]  # days/year
    stages = individual[2]       # ------
    columnDia = individual[3]    # m
    columnHt = individual[4]     # m
    shellTh = individual[5]      # mm
    insulationTh = individual[6] # mm
    plateTh = individual[7]      # mm
```

```
# dependent varable                                       unit
headTh = shellTh                                          # mm
holeDia = plateTh                                         # mm
towerCrossSecArea = np.pi*(columnDia**2)/4                # m^2
innerColDia = columnDia                                   # m
outerColDia = columnDia + 2*0.001*shellTh                 # m
insulatedColDia = outerColDia + 2*0.001*insulationTh # m

# Total amount of Steel we require in kg
M = ((0.37 * innerColDia + towerCrossSecArea) * 0.001 * plateTh * stages + np.pi * (innerColDia**2) * 0.001 * headTh + \
      0.6 * np.pi * ((outerColDia**2) - (innerColDia**2)) * columnHt) * (1.1 * densitySteel)

# Total amount of Asbestos we require in kg
A = np.pi * ((insulatedColDia**2) - (outerColDia**2)) * columnHt * densityAsbestos / 4

return (1000 * reboilerDuty * costSteam * workingDays * 24 * 3600) / (1000 * latentheatSteam) + (M * costSteel) + (A * costI
```

```
def roulettewheelSelection(p):
    r = random.random()
    cumsum = np.cumsum(p)
    y = (cumsum<r)
    x= [i for i in y if i==True]
    return len(x)-1

def crossover(parent1, parent2, varMin, varMax):
    # Range of the random generator. A random value will be sampled between -gamma and 1+gamma.
    # This sampled value will be used to perform a convex combination between parent1 and parent2
    gamma = 0.1
    nVar = len(parent1)
    alpha = np.random.uniform(-gamma, 1 + gamma, nVar)
    child1 = alpha * np.array(parent1) + (1 - alpha) * np.array(parent2)
    child2 = alpha * np.array(parent2) + (1 - alpha) * np.array(parent1)

    child1 = [varMin[i] if j<varMin[i] else j for i, j in zip(range(nVar), child1)]
    child1 = [varMax[i] if j>varMax[i] else j for i, j in zip(range(nVar), child1)]

    child2 = [varMin[i] if j<varMin[i] else j for i, j in zip(range(nVar), child2)]
    child2 = [varMax[i] if j>varMax[i] else j for i, j in zip(range(nVar), child2)]

    return [child1, child2]
```

```python
def mutate(child, varMin, varMax):

    nVar = len(child)
    mu_rate = 0.3
    nmutaion = int(mu_rate * nVar)
    index = np.random.randint(0 , nVar - 1, size = (1, nmutaion))[0].tolist()
    child = np.array(child)
    varMin = np.array(varMin)
    varMax = np.array(varMax)
    mutant = child
    normalrandom = child[index] + 0.1 * (varMax[index]-varMin[index]) * np.random.randn(1, len(index))[0]
    mutant[index] = normalrandom

    mutant = [varMin[i] if j<varMin[i] else j for i, j in zip(range(nVar), mutant)]
    mutant = [varMax[i] if j>varMax[i] else j for i, j in zip(range(nVar), mutant)]

    return mutant

varMin = [470, 325, 13, 0.3, 9, 8, 45, 3]
varMax = [530, 335, 25, 1.5, 15, 14, 55, 6]
nVar = 8               # number of decision varaibles
varSize = (1,nVar)

# GA parameters
maxGeneration= 350      # max generation number
nPop = 50                # number population

cP = 0.95            # crossover percentage
nCh = 2*round(cP*nPop/2) # number of offsprings = number of parents

beta = lambda reboilerDuty : 0.00000001*(reboilerDuty - 496)**2

# initialization
# class Individual:
#     position = []
#     cost = []
# population = [Individual() for individual in range(nPop)]
```

```python
beta = lambda reboilerDuty : 0.00000001*(reboilerDuty - 496)**2

# initialization
# class Individual:
#     position = []
#     cost = []
# population = [Individual() for individual in range(nPop)]

population = [[] for individual in range(nPop)]
populationCost = [[] for individual in range(nPop)]

for individual in range(nPop):
    for var in range(nVar):
        population[individual].append(round(random.uniform(varMin[var],varMax[var]),4))
    populationCost[individual] = totalCost(population[individual])

# sort population
sorted_index = np.argsort(populationCost)
populationCost = np.sort(populationCost).tolist()
population = [population[individual] for individual in sorted_index[0:nPop]]

# store best solution
bestSol = populationCost[0]
best_reboilerDuty = []
best_workingDays = []
best_stages = []
best_columnDia = []
best_columnHt = []
best_shellTh = []
best_insulationTh = []
best_plateTh = []
best_costMemory = []
```

```python
# generation loop
for generation in range(maxGeneration):

    # elitism
    nextGeneration = population[0:nPop-nCh]
    nextGenerationCost = populationCost[0:nPop-nCh]
    # crossover 2 parent => 2 child
    for reProduction in range(int(nCh/2)):

        # calculate selection probablity
        p = [(1 - 1 / (1 + math.exp(-beta(population[individual][0]) * populationCost[individual]))) for individual in range(nPo
        sump = sum(p)
        p = [elem/sump for elem in p]

        # select first parent
        index1 = roulettewheelSelection(p)
        parent1 = population[index1]

        # select second parent
        index2 = roulettewheelSelection(p)
        parent2 = population[index2]

        children = crossover(parent1, parent2, varMin, varMax)

        # mutation of child 1
        mutProb = random.random()
        if(mutProb <= 0.05):
            children[0] = mutate(children[0], varMin, varMax)

        # mutation of child 2
        mutProb = random.random()
        if(mutProb <= 0.05):
            children[1] = mutate(children[1], varMin, varMax)

        nextGeneration.extend(children)
        nextGenerationCost.extend([totalCost(child) for child in children])
```

```python
# sort next generation
sorted_index = np.argsort(nextGenerationCost)
nextGenerationCost = np.sort(nextGenerationCost).tolist()
nextGeneration = [nextGeneration[individual] for individual in sorted_index[0:nPop]]

# Replace the current population by the nextGeneration
population = nextGeneration
populationCost = nextGenerationCost

best_reboilerDuty.append(population[0][0])
best_workingDays.append(population[0][1])
best_stages.append(population[0][2])
best_columnDia.append(population[0][3])
best_columnHt.append(population[0][4])
best_shellTh.append(population[0][5])
best_insulationTh.append(population[0][6])
best_plateTh.append(population[0][7])
best_costMemory.append(populationCost[0])
```

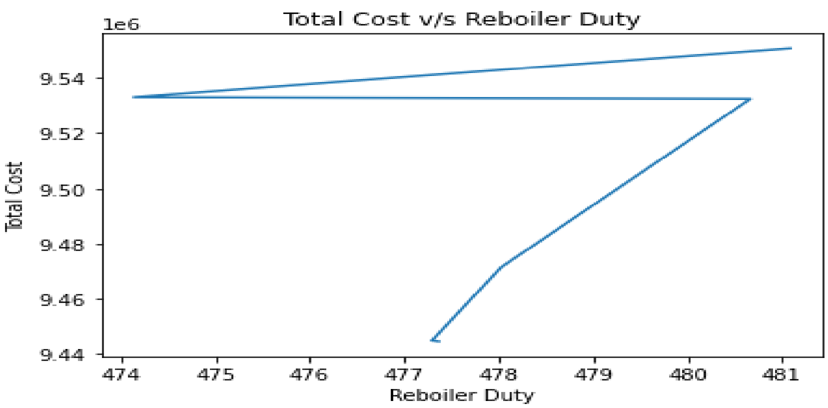
```python
print(population[0])
plt.plot(best_reboilerDuty, best_costMemory)
plt.title('Total Cost v/s Reboiler Duty')
plt.xlabel('Reboiler Duty')
plt.ylabel('Total Cost')
plt.show()

plt.plot(best_workingDays, best_costMemory)
plt.title('Total Cost v/s Working Days')
plt.xlabel('Working Days')
plt.ylabel('Total Cost')
plt.show()

plt.plot(best_stages, best_costMemory)
plt.title('Total Cost v/s Number of Stages')
plt.xlabel('Number of Stages')
plt.ylabel('Total Cost')
plt.show()

plt.plot(best_columnDia, best_costMemory)
plt.title('Total Cost v/s Column Diameter')
plt.xlabel('Column Diameter')
plt.ylabel('Total Cost')
plt.show()

plt.plot(best_columnHt, best_costMemory)
plt.title('Total Cost v/s Column Height')
plt.xlabel('Column Height')
plt.ylabel('Total Cost')
plt.show()

plt.plot(best_shellTh, best_costMemory)
plt.title('Total Cost v/s Shell Thickness')
plt.xlabel('Shell Thickness')
plt.ylabel('Total Cost')
plt.show()

plt.plot(best_insulationTh, best_costMemory)
plt.title('Total Cost v/s Insulation Thickness')
plt.xlabel('Insulation Thickness')
plt.ylabel('Total Cost')
plt.show()

plt.plot(best_plateTh, best_costMemory)
plt.title('Total Cost v/s Plate Thickness')
plt.xlabel('Plate Thickness')
plt.ylabel('Total Cost')
plt.show()
```

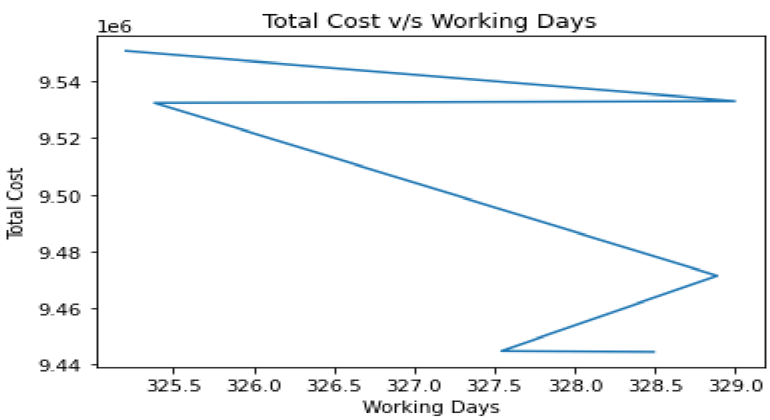
```python
print('Optimal Stages: ' + str(best_stages[maxGeneration - 1]))
print('Optimal Cost: ' + str(best_costMemory[maxGeneration - 1]))
```

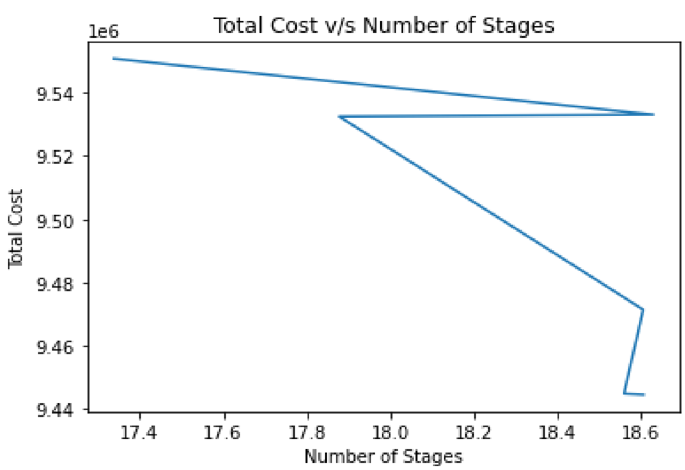
Optimal Phenotype (Sulution):->

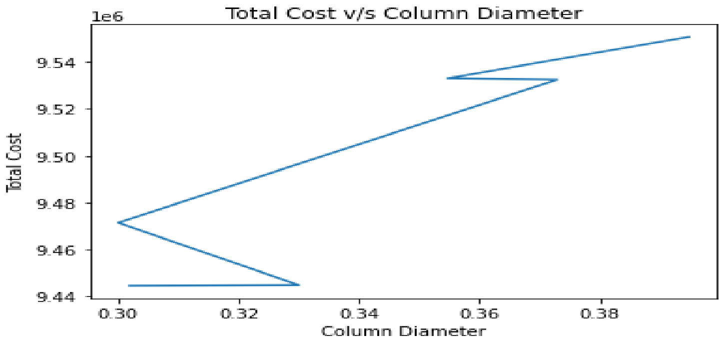
```
[477.3618781627051, 328.49017311596083, 18.606501193518543, 0.30191254136418, 12.279347312776242, 9.234570589385678, 48.58398
407288848, 4.191475646746474]
```

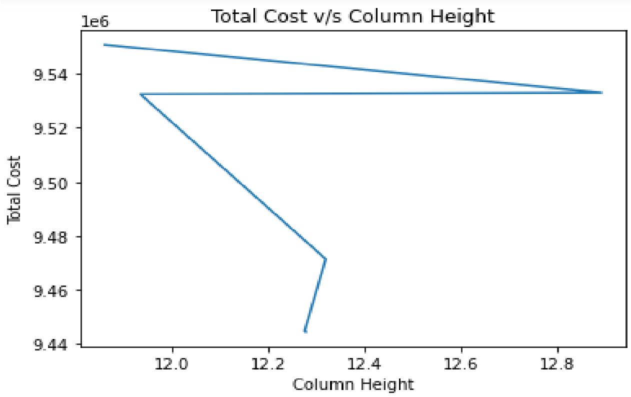
Various Plots for the Optimal Solution:->

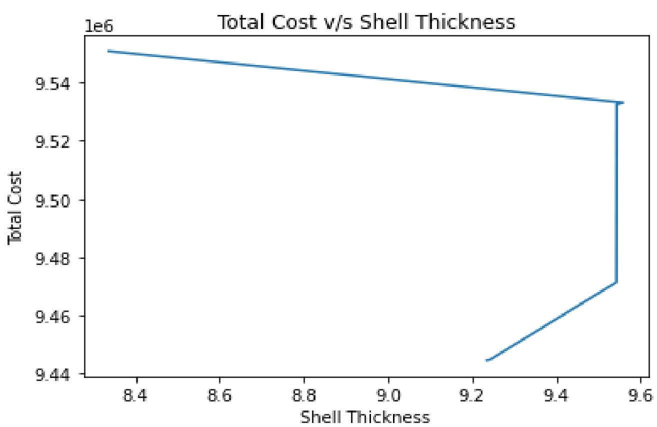


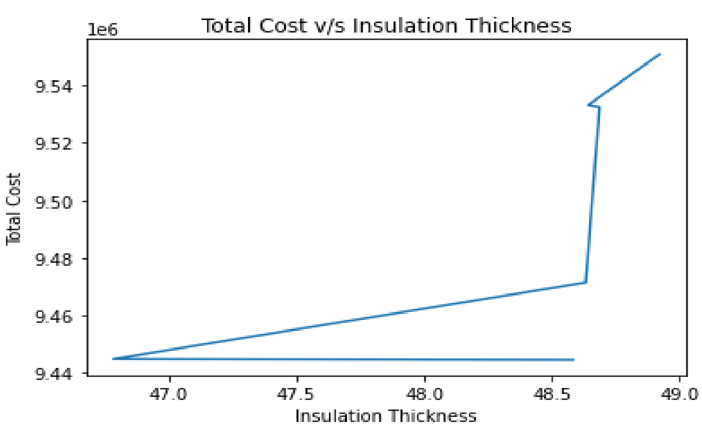


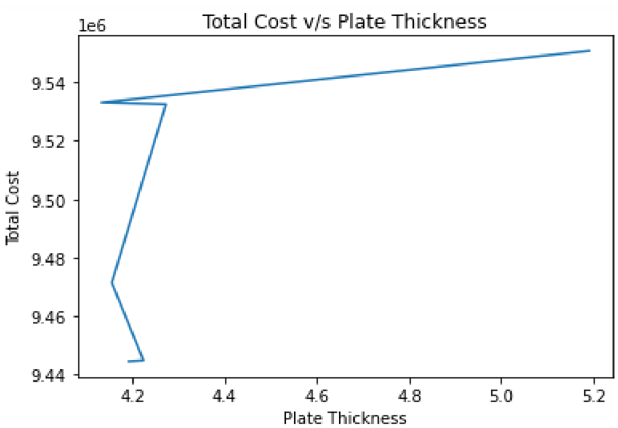



Total Cost v/s Column Diameter
1e6
9.54
9.52
9.50
9.48
9.46
9.44
Total Cost
0.30
0.32
0.34
0.36
0.38
Column Diameter


Total Cost v/s Column Height
1e6
9.54
9.52
9.50
9.48
9.46
9.44
Total Cost
12.0
12.2
12.4
12.6
12.8
Column Height


Total Cost v/s Shell Thickness
1e6
9.54
9.52
9.50
9.48
9.46
9.44
Total Cost
8.4
8.6
8.8
9.0
9.2
9.4
9.6
Shell Thickness


Total Cost v/s Insulation Thickness
1e6
9.54
9.52
9.50
9.48
9.46
9.44
Total Cost
47.0
47.5
48.0
48.5
49.0
Insulation Thickness



Final Result:->

```
Optimal Stages: 18.606501193518543
Optimal Cost: 9444510.841867816
```

Advantages of using Genetic Algorithms

The Genetic Algorithms are based on the mechanisms of natural selection and genetics, which play a dominant role in the Darwinian evolution of biological organisms. The Gas are known to be efficient in searching noisy, discontinuous and non-convex solution spaces, their characteristic features are:

- They are ‘zero’ order search techniques implying that they need only the scaler values of the objective function to be optimized.
- GA perform a global search, and hence, they mostly converge to (or in the vicinity of) the global optimum of the objective function.
- The search procedure used by the GAs is stochastic and hence they can be utilized without invoking ad-hoc assumptions, such as smoothness, differentiability and continuity, pertaining to the form of the objective function. Owing to this feature Gas can be used to solve optimization problems that cannot be conveniently solved using the classical gradient-based algorithms, which require the objective function to simultaneously satisfy the above criteria.
- The GA procedure can be effectively parallelized, which helps in efficiently searching a large multi-dimensional solution space.

SAFETY PRECAUTIONS AND RECOMMENDATIONS FOR OPERATING A DISTILLATION COLUMN

The operation of distillation in the industry is often associated with several hazards which have to be properly dealt with, to reduce the damage caused by them. Hazard identification is an essential part of the design of protection for pressure systems. The technique of hazard and operability (HAZOP) studies can be helpful in ensuring that all potential scenarios have been considered. A few of the hazards are pointed out below –

- Leakage in Reboiler tubes : Many distillation columns use steam to heat the process fluids. Generally the steam is at a higher pressure than the process and if the reboiler tubes develop a leak, then steam might enter the column to cause havoc is some situations.
- Improper piping management : Pipes and tubes are used throughout the industry. They are omnipresent. If proper care is not taken to maintain pressure difference, etc. along the pipes, then it might affect the flow parameters and efficiency of the process.
- Electrical power failure : Power loss can cause serious instruments to shutdown, hence there is a need for backing them up with UPS. Electrical failure may cause high-pressure zone generation in the condenser which may prove disastrous.
- Huge inventories : If a company stores huge inventories of flammable liquids which are to be sued in the distillation column, then proper care has to be taken to keep the nearby environment safe.
- Overpressure : Distillation column has a large input of heat energy at the reboiler and large output of heat energy at the condenser. If the cooling at condenser is lost, then overpressure may be developed in the column. In a single column, loss of cooling can occur not only due to malfunction of the condenser but also due to loss of reflux or of subcooled feed. Furthermore, the rapid expansion of the water as it flashes to steam can create very damaging overpressures.
- Underpressure : Loss of steam at the reboiler can create underpressure in the column.
- Flammable materials : If flammable materials get deposited in the column then, it may cause fire upon opening the column for maintenance work as air enters the column through the manways.

Thus, there are many such hazards which engineers must be aware of before operating the distillation column. Some of the ways in which we can prevent these hazards from occurring or reduce the impact as much as possible, are given below –

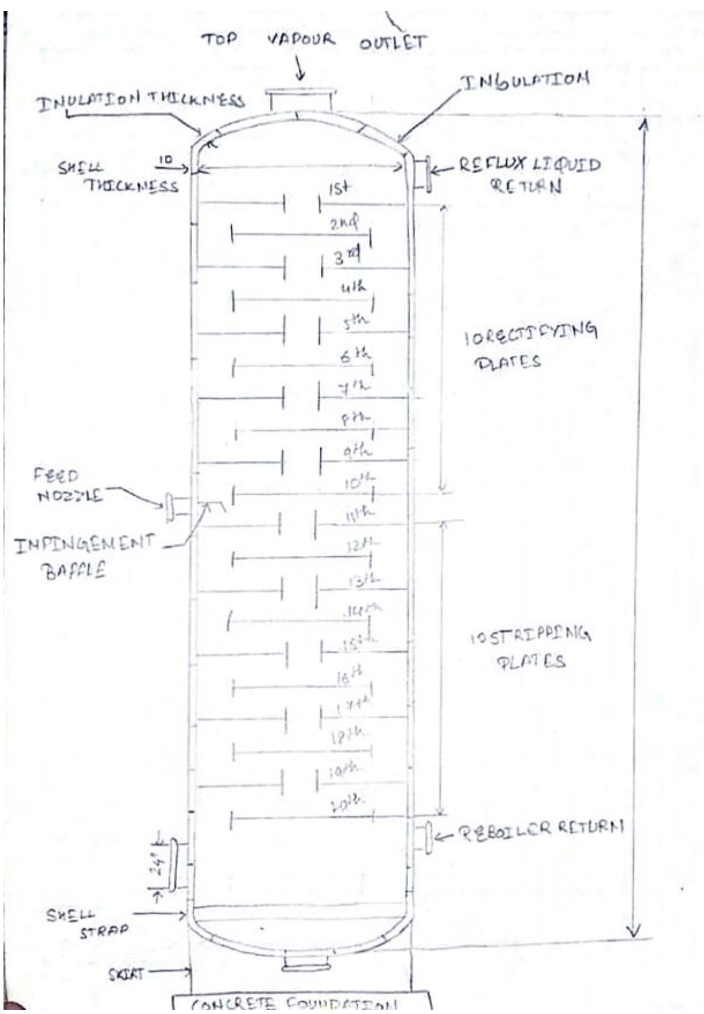
- Limiting the amount of inventory has always been the best way to reduce the hazard associated with the storage of flammable liquids used in the distillation column.
- Relief valves can be used to protect the column from damaging overpressure scenarios. Various high-tech and superior devices are being developed which are intelligent enough to sense the impending danger and alert the engineers way before the hazard occurs, thereby saving life and property.
- On columns operating at or near atmospheric pressure, full vacuum design, vacuum breakers, or inert gas injection is needed for protection.

Real life incidents are often a learning for us to make sure such incidents donot take place again. We can learn a lot of things from such disasters and it our responsibility to make processes and process conditions safe and secure for all the personnel working at the floor of the plant. One such incident is mentioned below –

In Antwerp, Belgium, 1989 - An explosion on an ethylene oxide distillation column caused a large fire which caused extensive damage throughout the plant.

Thus, process safety is indeed critical for any process operating in the plant and all the engineers and the technicians must be well-versed with the potential hazards associated with the process as well as immediate remedies and solutions to tackle the problems.

DISTILLATION COLUMN DIAGRAM



Contributions of Group members in the project –

Yash Balraj Ippakayal	18045135	Process Design, Mechanical Design, Simulation using DWSIM, Safety procedures, Cost computation
Mohit Punia	18045136	Design of Supports
Suraj Kumar Maurya	18045124	Process Design
Himanshu Pareek	18045138	Cost optimization using Genetic algorithms
Dilbwag Singh Bhamra	18045129	ANN based price modelling
Ashish Kumar Singh	18045139	Cost computation, Diagram of Distillation column

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