CHAPTER 6

Design

6.1. Distillation design:

6.1.1. Introduction:

Distillation is most common class of separation processes and properly of the better-understand unit operation that uses the difference in relative volatilities , or differences in boiling of the component to be separated, it is the most widely used method of separation in the process industries

-Types of distillation column:

1- Single flash vaporization.

2- Packed towers.

3- Plates towers.

a) Bubble cap towers.

b) Sieve pates.

c) Valve plates towers.

-Sieve trays: Sieve trays offer several advantage over bubble-cap trays , and their simpler and cheaper construction has led to their increasing use . the general form of the flow on a sieve tray is typical of a cross flow system with perforation in the tray taking the place of the more complex bubble caps . the key differences in operation between these two types of tray should be noted . with the sieve tray the vapor passes vertically through the holes into the liquid on the tray , where as with the bubble cap the vapor issues in an approximately horizontal direction from the slots . with the sieve plate the vapor velocity through the perforation must be greater than a certain minimum value in order to prevent the weeping of the liquid stream down through the holes . at the other extreme , a very high vapor velocity leads to excessive entrainment and loss off tray efficiency .

6.1.2. Collect the data of fluid to be distillated and distillated fluids:

-Feed stream:

At 403^0 K, 2000 KPa.

Table (6.1) feed stream composition.

Component	Mole flow (kmol/h)	Mole%	Mass flow (kg/h)	Wt%
methanol	2516.10	0.217006616	80615.844	0.125340067
isobutylene	428.05	0.036918138	24017.8855	0.037342577
1-butene	1817.511622	0.156755275	101977.3431	0.158552542
2-butene	5172.917692	0.44614963	290236.8929	0.451255111
MTBE	1660.00	0.14317034	146329	0.227509702
water	0	0	0	0
Total	11594.58	1	643176.9655	1

-Top product stream :

At400 ^{o} K, 1900KPa.

Table (6.2) top stream composition

Component	Mole flow (kmol/h)	Mole%	Mass flow (kg/h)	Wt%
methanol	2428.7308	0.246641613	77816.57994	0.157508615
isobutylene	428.0505	0.0434689	24017.914	0.0486161
1-butene	1817.512	0.1845792	101975.46	0.2064048
2-butene	5172.912	0.5253107	290236.83	0.5874676
MTBEs	0	0	0	0
water	0	0	0	0
Total	9847.236	1	494046.06	1

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-Bottom product stream:

At 440 ^{o} K, 1925.175 KPa

Table (6.3) bottom stream composition

Component	Mole flow (kmol/h)	Mole%	Mass flow (kg/h)	Wt%
methanol	87.36842105	0.05	2799.284211	0.018770981
isobutylene	0	0	0	0
1-butene	0	0	0	0
2-butene	0	0	0	0
MTBE	1660	0.95	146329	0.981229019
water	0	0	0	0
Total	1747.368421	1	149128.2842	1

-Relative volatility:

Table (6.4) average relative volatility of composition.

Component	αfeed	αtop	αbottom	Aav
methanol	1.186110097	1.162297499	1.448866438	1.265758
isobutylene	4.214615978	4.270349142	3.743897719	4.076288
1-butene	4.281515808	4.345063797	3.73236071	4.119647
2-butene	3.479708054	3.515657126	3.194453855	3.396606
MTBE	1	1	1	1
water	0.381770611	0.369823631	0.51937441	0.423656

6.1.3. Heavy and light key:

Heavy key: mtbe

Light key: methanol.

6.1.4. Type of tray:

Sieve tray.

6.1.5. Determination of minimum reflux ratio:

$$\sum \frac{\alpha x}{\alpha - \emptyset} = Rm + 1 \longrightarrow \quad (1)$$

α= average Relative volatility of any component.

X= mole faction of component in Distillate.

Ø= Constant.

Rm = Minimum reflux ratio.

$$\sum \frac{\alpha\, zf}{\alpha - \emptyset} = 1 - q \longrightarrow \quad (2)$$

Where:

Zf= mole faction of component in feed stream.

q= feed quality

$$q = \frac{HG - HF}{HG - HL}$$

Where:

HG=Enthalpy of gas at the feed dew point (KJ/Kmol)

HL=Enthalpy of liquid at the feed bubble point (KJ/Kmol)

HF=Enthalpy of feed at 403^o K.

$q = \frac{1.91827-1.4672}{1.91827-1.67614} = 1.86$

Subustitute in equation (2) to find(Ø)

$\sum \frac{\alpha\ zf}{\alpha - Ø}$=1-1.86

$\sum \frac{\alpha\ zf}{\alpha - Ø} = -.86$

$$\frac{1.265758\times0.217007}{1.265758-Ø} + \frac{4.076288\times0.036918}{4.076288-Ø} + \frac{4.119647\times0.156755}{4.119647-Ø} + \frac{3.396606\times0.44615}{3.396606-Ø} + \frac{1\times0.14317}{1-Ø} + \frac{.423656\times0}{.423656-Ø} = 0$$

Solving Ø By try &error:

Ø =1.047365

Substitute in equation (1)to find Rm:

$$\frac{1.265758\times.246641613}{1.265758-Ø} + \frac{4.076288\times.043469189}{4.076288-Ø} + \frac{4.119647\times.184571192}{4.119647-Ø} + \frac{3.396606\times.525318007}{3.396606-Ø} + \frac{1\times0}{1-Ø} + \frac{.423656\times0}{.423656-Ø} = Rm+1$$

Rm= 1.494995

6.1.6. Calculation of the actual ratio(R)

The rule of thumb is:

$R = (1.2 \text{ ------- } 1.5)\ R_{min}$

R=1.2Rm

=1.2×1.5 = 1.8

6.1.7. Calculation of the minimum number of theoretical stages:

$$N_{min} = \frac{\text{Ln}\left(\frac{X_{lk}}{X_{hk}}\right)_D \times \left(\frac{X_{hk}}{X_{lk}}\right)_B}{\text{Ln}\alpha_{lk}}$$

Where:

X_{lk}=mole fraction of light key.

X_{hk}= mole fraction of heavy key.

α_{lk}= average relative volatility of light key.

Nmin= 26 stagess

6.1.8. Calculation of the number of theoretical stages:

$$N - N_{min} \Big/ N+1 = 0.75\left[1-\left(R-R_{min} \Big/ R+1\right)^{0.566}\right]$$

$\frac{\text{R}-\text{Rmin}}{R+1}=\frac{1.8-1.5}{1.8+1} = 0.1$

From Gilland relation.

$\frac{\text{N}-\text{Nmin}}{N+1}$ =0.54

N=57.695 stages

6.1.9. Calculation of the column efficiency ($E_{\circ}$):

$E_{\circ}$= 0.5278-0.27511 log(αlk*μF)+0.04493(log(αlk* μF))2

μF=0.2161

$E_{\circ}$=69.29%

6.1.10. Calculation of the number of actual stages (Na):

Na=$\frac{\text{N}}{E_{\circ}}$

=$\frac{57.695}{0.6929} = 83.265\ stages$

6.1.11. Calculation of the height of the column (Ht):

Ht=N×C+$\frac{(\text{N}-1)\times\text{c}}{10} + 0.2 \times Ht$

C: tray spacing = 0.609(so as to ensue accessibility for cleaning)

0.8Ht= 84×0.3+$\frac{(84-1)\times 0.3}{10} = 27.69$

Ht=34.6 m .

6.1.12. Determination of the feed plate location (m):

$$\frac{\text{n}}{m} = \left[\left(\frac{\text{zhk}}{zlk}\right) f \times \left(\frac{\text{xlk}}{xhk}\right)_D^2 \times \frac{\text{B}}{D}\right] 0.206$$

D=9847.2118Kmol/h B=1747.368 Kmol/h

$$\frac{\text{n}}{m} = \left[\left(\frac{0.14317034}{0.217006616}\right)_f \times \left(\frac{0.2396416}{0.007}\right)_D^2 \times \frac{1747.368}{9847.2118}\right]^{0.206} = 2.7561$$

m=$\frac{\text{N}}{1+\frac{\text{n}}{m}} = \frac{84}{1+2.7561} = 22.36\ \ stages \approx 22$

m=22 stage

the feed enter the column at tray no 22 from the Bottom.

6.1.13. Calculation of the tower diameter(D):

The following areas terms are used in the plate design procedure:

At=Total column cross- sectional area,

Ad=cross-sectional area of down comer,

An=Net area available for vapor-liquid disengement , normally equal to Ac-Ad for asingle pass plate,

Aa= Active or bubbing , area, equal to Ac-2Ad for single- pass plates,

Ao=Hole area, the total area of all the active holes,

Ap= perforated area (including blanked areas),

Aap= The clearance area under the down comer apron.

-Top diameter calculation:

U_F=K$\sqrt{\frac{\rho_L-\rho_V}{\rho_V}}$

Where:

U_F= floading vapor velocity (m/s) based on the net column cross sectional area A_n.

K=constant obtained from figure(1)appendix (A)

F_{LV}=$\frac{\bar{L}}{\bar{V}}\sqrt{\frac{\rho V}{\rho L}}$

Where:

F_{LV}=The vapor liguid flow factor in figer (1) appendix

$\bar{L}$ = Liguid mass flow rate kg/s

$\bar{V}$ =Vapor mass flow rate kg/s

Top Diameter calculations:

$$\frac{\bar{L}}{\bar{V}} = \frac{R}{R+1} = \frac{1.8}{1.8+1} = 0.64$$

From ideal gas law:

PV= nRT

$\boldsymbol{\rho}$v = $\frac{T_o\ P\ M_{wt}}{T\ P_o\ V_o}$ = $\frac{273.5\times19\times50.17}{400\times1\times22.4}$ = 29.09 Kg/m^3

F_{LV}= 0.64$\sqrt{\frac{29.09}{467.37}}$ =0.160

From figuer (1) appendix (A)

K=0.05

U_F=0.05×$\sqrt{\frac{467.37-29.09}{29.09}}$ = 0.753

Design velocity (U)= 80% of (U_F)

U = 0.8* 0.753 = 0.602 m/s

$A_n = \frac{V1}{\rho v \times U \times 3600} = \frac{(1+R)D}{\rho v \times U \times 3600} = \frac{(1+1.8)\times 9847.2118}{29.09\times 0.602\times 3600} = 0.437 m^2$

A_d = 0.12 A_t

$A_n = A_t - 0.12A_t = 0.88\ A_t$

$A_t = \frac{A_n}{0.88} = \frac{0.437}{0.88} = 0.496 m^2$

D = $\left(\frac{4A_t}{\pi}\right)^{0.5}$ = 0.79m

-Bottom diameter calculations:

$\bar{L}$ = (q×F) + L

From Ideal gas law:

PV= nRT

$\boldsymbol{\rho}$v = $\frac{T_o\ P\ M_{wt}}{T\ P_o\ V_o} = \frac{273.15\times 19.252\times 85.34}{440\times 1\times 22.4}$ = 45.53

F_{LV}= 1.046$\sqrt{\frac{45.53}{728.228}}$ = 0.261

From figure (1) appendix (A) at FLV= O.261 and spacing 60 mm

K=0.046

U_F=0.046×$\sqrt{\frac{728.228-45.53}{45.53}}$ = 0.178m/s

Design velocity (U)= 80% of flooding velocity(U_F)

0.8× 0.178 = 0.1424m/s

$A_n = \frac{V}{\rho V \times U \times 3600} = \frac{27572.19}{45.53\times 0.1424\times 3600} = 1.198 m^2$

Down comer area =12% from total area=0.88A_t

$A_t = \frac{A_n}{0.88} = \frac{1.198}{.88} = 1.36 m^2$

D=$\left(\frac{4At}{\pi}\right)^{0.5}$=$\left(\frac{4\times 1.36}{3.14}\right)^{0.5}$= 1.3172 m.

Taking the bottom diameter for the entire tower since it is the greatest diameter.

A_t = 1.36 m^2

A_d = 0.12A_t

=0.12×1.36=0.1632 m^2

$A_a = A_t - 2A_d$

$= 1.36 - 2(0.1632) = 1.0336 m^2$.

$A_o = 0.1 \times A_a = 0.10336 m^2$.

$A_c = 0.07 \times A_t = 0.07 \times 1.36 = 0.0952 m^2$.

-A_p=Preformatted area:

When down comer area = 0.12× A_t

$\frac{LW}{D} = 0.75$(From figure (4) appendix (A)&Θ_C =98^O(from figure(5)appendix (A))

Wherer L_W : Weir length.

L_W =0.75×D= 0.75 × 1.3172=0.9879 M

Angle subtended at plate edge by imperforated strip=180- 98=82^o

Calming zones width=50mm

Mean Length, imperforated edage strips

$=(1.3172 - 50\times10^{-3})\pi \times\left(\frac{82}{180}\right) = 1.813$ m.

Area of imperforated edge strips= $50 * 10^{-3} \times 1.813 = 0.0906\ m^2$.

Mean length of calming zone = $(1.3172 - 50*10^{-3})\sin\left(\frac{98}{2}\right) = 0.9563 m$

Area of calming zone $=2(0.9563*50*10^{-3}) = 0.09563 m^2$

Total area for perforatins, $A_p = 1.336 - 0.0906 - 0.09563 = 0.8473 m^2$

$\frac{A_0}{A_p} = 0.1\left(\frac{A_a}{A_p}\right) = 0.1\left(\frac{1.0336}{0.8473}\right) = 0.12198$.

$\frac{A_0}{A_p} = 0.9\left(\frac{d_0}{L_p}\right)^2$

Where L_p:hole pitch.

$0.12198 = 0.9\left(\frac{d_0}{L_p}\right)^2$

$\left(\frac{d_0}{L_p}\right)^2 = 0.1355$

$\left(\frac{L_p}{d_0}\right) = 2.716$.

2.716 are satisfactory, within 2.5 to 4.0.

6.1.14. Determination of fractional entrainment (ϕ):

From figure (2) appendix (A)

$At\ F_{LV}$=0.261 and 80% flooding ϕ= 0.09(well below 0.1).

e=$\frac{\phi \times L}{1-\phi}$ = $\frac{0.009\times 17724.98}{1-0.009}$ = 160.973kg/h.

6.1.15. Weeping point:

Weeping will occur when U_O(min) < U_o(min) calculated.

$U_o = \frac{V}{\rho V \times A_o} = \frac{37543.53194}{45.53\times 0.10336\times 3600} = 2.3175$m/s

Taking 70% turn down.

U_o(min) = 0.7×U_o= 0.7 ×2.3175 = 1.624 m/s.

U_O(min) calculated = $\frac{k_2 - 0.9(25.4 - d_o)}{\rho_v^{0.5}}$

d_o=5 mm

$k_2$is a function of ($h_w + h_{ow}$(min))

h_w:weir hight = 23 mm

h_{ow}(min):minimum weir crest =750×$\left(\frac{L_{min}}{\rho_l L_W}\right)^{2/3}$

L_{min}= o.7×17724.98 = 12407.486kg/h.

h_{ow}(min)=750 ×$\left(\frac{12407.486}{728.228\times 0.9879\times 3600}\right)^{2/3}$=21.31

h_w+h_{ow}(min)=23+21.31= 44.31mm.

From figure (3) appendix (A)

k_2=30

U_O(min)calculated=$\frac{30-0.9(25.4-5)}{(45.53)^{0.5}}$= 1.5m/s.

∴Weeping will not occur.

6.1.16. Pressure drop calculation:

ΔP=9.81 ×h_t ×10^{-3}×ρ_l

h_t =h_d+(h_w+h_{ow})+h_r

$h_d = 51\left(\frac{U_O}{C_O}\right)^2 \frac{\rho_V}{\rho_l}$

From figure (6)appendix (A)

$At\ \frac{A_O}{A_P}$=12.198%&$\frac{plate\ thicness}{hole\ thicness}$=1

C_O=0.859

h_d =51$\left(\frac{2.3175}{0.859}\right)^2 \frac{45.53}{728.228}$=23.208mm.

h_{ow}(min)=750 ×$\left(\frac{27503.63}{728.228\times0.9879\times3600}\right)^{2/3}$=36.23mm.

h_w=23mm

h_r=$\frac{12.5\times10^3}{\rho_l}$=$\frac{12.5\times10^3}{728.228}$=17.16

h_t=21.31+36.23+23+17.16=97.7mm

ΔP=9.81 ×97.7×10^{-3}×728.228=0.007 bar/tray.

6.1.17. Down comer liquid back up:

For safe design and to avoid flooding

h_b<$\frac{1}{2}$(C+h_w)

h_b=$h_t + h_d + h_w + h_{ow} + h_r + h_{dc}$

h_{dc}=166$\left(\frac{L}{\rho_l A_{ap}}\right)^2$

A_{ap}=h_{ap}×L_W

h_{ap}=h_W-10mm

23-10=13mm

A_{ap}=0.9879 ×10^{-3}×13=0.013mm

h_{dc}=166$\left(\frac{17724.98}{728.228\times 0.013\times 3600}\right)^2$=4.64mm

h_b=97.7+36.23+23+4.67=201.83mm

$\frac{1}{2}$(C+h_w)= $\frac{1}{2}$(0.3+23×10^{-3})=0.323m.

h_b<$\frac{1}{2}$(C+h_w) no floading will occure.

6.1.18. Down comer residence time:

t_r=$\frac{A_d h_b \rho_l}{L}$

=$\frac{0.1632\times0.2018\times728.228}{(17724.98/3600)}$= 4.8 sec.

4.8>3 so it is acceptaple.

6.1.19, Thickness calculation:

- columan thickness:

Highest operating temperature is 166.85^0C.

Design stress at 166.85^0C = 111 N/mm^2.

Joint efficiency = 0.85.

e = $\frac{P_i D_i}{2Jf - P_i}$

= $\frac{1925175 \times 1.3172}{2 \times 111 \times 10^6 \times .85 - 1925175} = 0.01357$mm.

Corrosion allowance 2mm.

$\therefore\ column\ thickness = 2.01357mm.$

-Head thickness:

- Ellipsoidal heads:

e = $\frac{P_i D_i}{2Jf - 0.2P_i}$

= $\frac{1925175 \times 1.3172}{2 \times 111 \times 10^6 \times .85 - 1925175}$ = 0.011m.

-Tori spherical head

e = $\frac{P_i C_s R_c}{2Jf - (C_s - 0.2)}$

$C_s \equiv stress\ cocentration\ factor\ for\ torispherical\ head.$

$C_s = \frac{1}{4}(3 + \sqrt{R_c/R_k}\ )$

$R_c \equiv crown\ radius.$

$\frac{R_c}{R_k} = no\ less\ than\ 0.6.$

$R_k \equiv knukle\ radius.$

$R_c\ \equiv\ D_i$

$R_k \equiv 0.6D_i.$

$C_s = \frac{1}{4}(3 + \sqrt{1/0.6}\ )$ = 1.072.

J =1(No joint in head).

E = $\frac{1925175 \times 1.072 \times 1.3172}{2 \times 111 \times 10^6 + (1.072 - 0.2)}$ = 0.01224mm.

Ellipsoidal heads IS recommended since it has the smallest thickness

$\therefore\ head\ thickness = 0.011mm.$

Table (6.5) summary of design calculation.

Parameter	Value
Tower diameter	1.3172M
Tray **spacing**	0.30
Tower Height	34.6M
Total area(cross sectional area)	1.36m^2
Down comer area	0.1632m^2
Net area	1.19m^2
Active area	1.0336m^2
Hole area	0.10336m^2
Number of theoretical stages	57.695 stages
Tower efficiency	69.29%
Plate thickness	0.005M
Weir height	0.005M
Weir length	0.987M
Hole diameter	0.005M
Fractional entrainment	0.09
Weeping velocity	1.5M/S
Total presser drop head	0.007 bar
thickness Of column	2.01357MM
thickness Of head	0.011MM

6.2. Reactor design:

-Type of reactor proposed:

A packed bed reactor, which is essentially a plug flow reactor packed of solid catalyst particles to speed up the reaction.

-Justification of selection:

- Adiabatic packed bed reactor, is the cheapest type of reactors and simple to design and construction.
- It give the highest conversion per weight of catalyst of any catalyst reactor.
- Running the reactor adiabatically allows to recover heat from the high temperature product and reduce cost of energy.

"The process uses an acidic ion-exchange-resin catalyst."

6.2.1. Design calculation:

$(CH_3)_2C{=}CH_2 + CH_3OH \rightarrow (CH_3)_3C\text{-}O\text{-}CH_3$

Conversion: 80% of isobutylene.

-Input and output stream:

Table (6.6) Summary of material balance around reactor.

Component	Input(Kmol/h)	Output(Kmol/h)
Methanol	4176.10	2516.10
Isobutylene	2088.05	428.05
1-butene	1817.511622	1817.511622
2-butene	5172.917692	5172.917692
Mtbe	0.00	1660.00
water	0.00	0.00
Total	13254.58	11594.58

-Rate law:

$$-r_A = k_f \frac{C_{isobutylene}}{C_{methanol}} - k_r \frac{C_{mtbe}}{C^2{}_{methanol}}$$

Where:

$$k_{r=}1.464 \times 10^{22} \exp\left(-\frac{129{,}600}{RT}\right)$$

$$k_f = 6.05 \times 10^{16} \exp\left(-\frac{85{,}400}{RT}\right)$$

$$C_{isobutylene} = C_{A_O}(1 - X_A)$$

$$C_{methanol} = C_{A_O}(\theta_{meth} - X_A)$$

$$C_{mtbe} = C_{A_O}(\theta_{mtbe} + X_A)$$

"The units of reaction rate, ri, are mol/m3h, and the activation energy is in J/mol."

Design equation:

$$\frac{dF_A}{dV} = F_{A_O}\left(\frac{dX_A}{dV}\right) = -r_A = k_f \frac{C_{isobutylene}}{C_{methanol}} - k_r \frac{C_{mtbe}}{C^2{}_{methanol}}$$

$$dV = \frac{F_{A_O}}{k_f \frac{C_{isobutylene}}{C_{methanol}} - k_r \frac{C_{mtbe}}{C^2_{methanol}}} dX_A \longrightarrow (1)$$

$$\int_0^V dV = F_{A_O} \int_0^{0.8} \frac{dX_A}{k_f \frac{C_{isobutylene}}{C_{methanol}} - k_r \frac{C_{mtbe}}{C^2_{methanol}}} \longrightarrow (2)$$

- Integration of right side of equation (2)

Since the reactor is adiabatic, temperature (T) and conversion(X) are related by the following equation:

$$X_A = \frac{\sum \theta_i C_{pi} (T - T_0)}{-\Delta H_{RX}}$$

Calculations were made by using Excel, and data need is constructed with the aid of equation (2), and tabulated in table (6.7):

Table (6.7) relation between conversion & temperature

T	X	F(x)
358.0001	0	0.095535
362.5341	0.091711	0.070099
367.0681	0.180646	0.05221
371.6021	0.26688	0.039508
376.1361	0.350477	0.030415
380.6701	4.31E-01	0.023869
385.204	5.10E-01	0.019149
389.738	0.586016	0.015773
394.272	0.659605	0.013431
398.806	0.730798	0.011961
403.34	0.79963	0.011381

These data are plotted in figure (6.1) below:

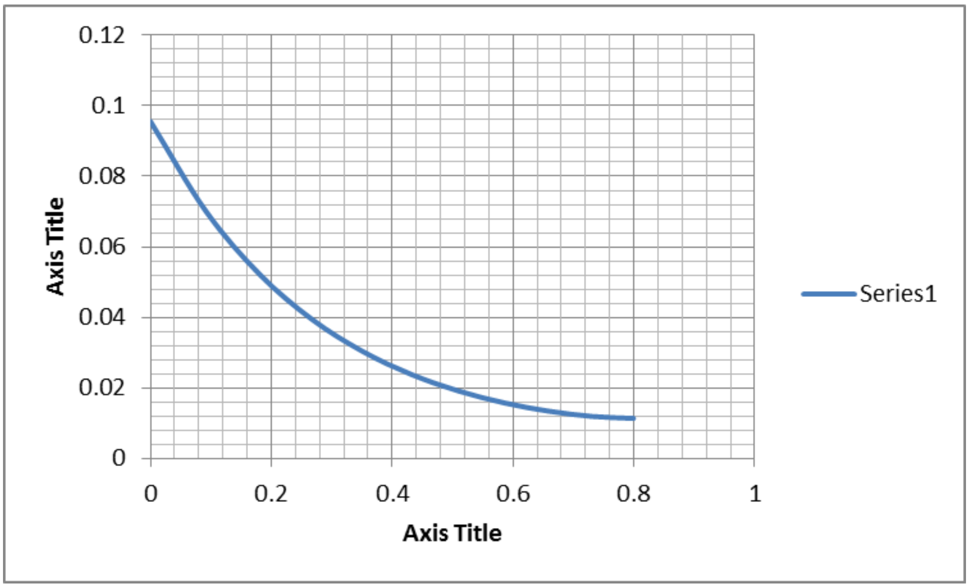

Figure (6.1) integration plot.

The area under the curve A = 0.031534679

$\therefore \frac{V}{F_{A_O}}$ = A

$\rightarrow \quad V = F_{A_O} \times A$

V = 2088.05 ×0.031534679 = 65 m^3

V = $\frac{\pi D^2 L}{4}$

Put L =13.8D

V= $\frac{\pi D^2 \times 13.8D}{4}$

$\rightarrow \quad D = \sqrt[3]{\frac{V}{10.8}} = \sqrt[3]{\frac{65}{10.8}}$ =1.8m.

L = 13.8×1.8 = 24.8m.

-Reactor thickness:

Highest operating temperature is 403°K

Design stress at 403°K = 70 N/mm^2

e = $\frac{P_i D_i}{2Jf - P_i}$

$$\frac{1925175 \times 1.8}{2 \times 70 \times 10^6 \times 0.85 - 1925175} = 29.59$$

Corrosion allowance 2mm.

∴ Reactor thickness =31.59mm.