Design of equipments

MAJOR EQUIPMENT DESIGN:

Design of the reactor for nitration:

Thermodynamics and experimental data indicate that the equilibrium constant is very large for the nitration of aromatics, under liquid phase conditions. The reverse reaction can be neglected and the following rate equation can be obtained provided that the agitation is sufficient to approximate the equilibrium distribution between the phases. The rate expression is given as follows:

$$r = k.x_{Aa}\, x_{Bb}\, \gamma_{Aa}\, \gamma_{Bb}\, (V_a + V_b K')$$

(Obtained from Hougen and Watson volume – 3, page No. 1055).

Where,

X_{Aa}- Mole fraction of Nitric acid in acid phase.

X_{Bb} – Mole fraction of aromatic in organic phase.

V_a - Volume fraction of acid phase

V_b – Volume fraction of organic phase

K'-0.14

k– rate constant.

'k' is given by

$$Lnk = (-E/RT) + A;$$

E – activation energy

= 14,000 Cal/gm.

A is the constant (Arhaneous constant)

= 26.22 gm moles / hr / lit of combined phase.

'R' is the gas constant

= 1.987.cal/gm mol / ^{0}K

'T' is the reaction temperature in ^{0}K= 323^{0}K

γ_{Aa} is activity coefficient of mixed acid.

γ_{Bb} is activity coefficient of chlorobenzene in organic phase.

And γ_{Bb} is given by

$$\gamma_{Bb} = 1 + 62 \quad X_{Aa} \, (x_{sb})^{(1+40XAa)}$$

Where X_{sb} is mole fraction of nitrochlorobenzene in the organic phase.

X_{Aa} is mole fraction of nitric acid in the acid phase.

Mixed acid

Mixed acid requirement = 679.4 kg/hr.

= 16316 kg/day

	Weight %	Mole %
Nitric acid	35.5	31.9
Sulphuric acid	52.5	30.35
Water	12	37.75

Average molecular weight, M

$$= \frac{100}{\left(\frac{35.5}{63} + \frac{52.5}{98} + \frac{12}{18}\right)}$$

= 56.62 kg/K mol

Basis:

100-gram moles of chlorobenzene charged.

It requires 100-gram moles of Nitric acid

= 6320 grams of HNO_3

Nitric acid fed = 1.02 x 6320

= 6446.49

$$\text{Weight of mixed acid} = \frac{6446.4}{0.355}$$

= 18159 grams.

From fig 211(Hougen and Watson volume 3,page no. 1067)

Density of mixed acid

$$\sum x\rho = 1.7 \text{ gm/c.c}$$

$$\text{Volume of mixed acid} = \frac{18159}{1.7x10^3}$$

$$= 10.88 \text{ lit.}$$

Density of chlorobenzene = 1.107 gm/c.c

$$= 1107 \text{ kg/m}^3$$

$$\text{Volume of chlorobenzene} = \frac{112.5x10^2}{1.107x10^3}$$

$$= 10.16 \text{ lit.}$$

Therefore total volume = 10.16 + 10.68

= 20.84 lit.

Volume fraction of mixed acid, Va = (10.68) / (20.84).

= 0.512

Volume fraction of chlorobenzene Vb = 1- 0.512

= 0.488

lnk = -E/(RT) + A

= [-14,000/(1.987x323)] + 26.22

lnk = 4.406

k = 81.97

Initial value of K (Va+K'Vb)

= 81.90 (0.512 + 0.14 x 0.488)

= 47.55

After reaction takes place, assuming a conversion of 98% of conversion

V_b^1 = Volume of chlorobenzene + Volume of Nitrochlorobenzene.

=

Where

1298 kg/m^3 is density of p – isomer and 1343 kg/m^3 is density of o- isomer.

V_b^1 = 0.203 + 11.74

= 11.95 lit.

In the acid phase:

Sulphuric acid = 18159 x 0.525 = 9533.47 g

Nitric acid = 6446.4 – 98 x 63.2 = 252.8 g

Water = 18159 x 0.12 + 98 x 18 = 3943.1 g.

Therefore total amount of acid mixture.

= 9533.47+252.8 + 3943.1

= 13729.37 g

Which corresponds to

Sulphuric acid = 69.4% (weight)

Nitric acid = 1.8% (weight)

Water = 28.8% (weight)

Density of mixed acid at this composition = 1.63 gm / cc.

Acid Volume = 13729.1 / 1630 = 8.42 lit.

∴Total volume v = 8.42 + 11.95

= 20.37 lit

Volume fraction of acid Va = 8.42/ 20.37

= 0.413

Volume fraction of chlorobenzene Vb = 1 - 0.413

= 0.587

∴Final value of $K(Va + K'V_b)$

= 81.71(0.413 + 0.14 x 0.587)

= 40.5 lit

Taking average value of

$K = (V_a + K'V_b)$

= (47.55 + 40.5)/2

= 44

We have taken average value of $(Va+V_bk^1)$

Which means that ($V_a+V_b k^1$) remains constant at the arithmetic average of the initial and final values. This assumption neglects the small variation in volume accompanying the reaction as a result of changes in densities or miscibility.

Nitration of chlorobenzene:

Basis: 100 gm moles of chlorobenzene:

Percentage conversion (100 x_{Sb})	X_{Bb}	X_{Aa}	γ_{Aa}	γ_{Bb}	$-r_A$	$-1/r_A$
0	1.0	0.319	24	1	336	2.96×10^{-3}
5	0.95	0.303	25	1	317	3.15×10^{-3}
10	0.9	0.2871	26	1	295	3.38×10^{-3}
20	0.8	0.2552	26	1	233	4.28×10^{-3}
30	0.7	0.2233	26	1	179	5.6×10^{-3}
40	0.6	0.1914	27	1.004	137	7.3×10^{-3}
50	0.5	0.1595	27	1.06	100	10×10^{-3}
60	0.4	0.1276	27	1.35	82	0.0122
70	0.3	0.0957	27	2.06	70	0.0142

80	0.2	0.0638	27	2.79	42	0.0236
90	0.1	0.0319	28	2.56	10	0.1
92	0.08	0.02552	28	2.33	4.4	0.22
94	0.06	0.01914	28	2.06	2.91	0.343
96	0.04	0.01276	28	1.74	1.092	0.91
98	0.02	0.00638	28	1.38	0.21	4.6

Assuming up to 0.5 conversion takes place in MFR portion and 0.5 to 0.98 conversion takes place in PFR portion

Using Simpson's 1/3rd rule

$V_1/F_{AO} = \Delta X_{Bb}/3[1/(-r_1) + 4/(-r_2) + 2/(-r_3) + \ldots 4/(-r_{n-1}) + 1/(-r_n])]$

Where

V_1 is the volume of reactor corresponding to PFR portion. F_{AO} is moles fed per hour.

$$F_{AO} = \frac{\text{Mass flow rate of feed}}{\text{Average molecular weight}}$$

Mass flow rate of feed = (467.02+707.8)

= 1174.82 Kg/hr.

Average molecular weight = 1174.82/ [(467.02)/(112.5) + (1707.8) / (56.62)]

= 70.55 gm/gm mole.

F_{AO} = (1174.82 x 1000) / (70.55)

= 16652 gmol / hr.

$\therefore V_1/F_{AO}$ = (0.1/3) [0.01 + 4 x 0.0122 + 2 x 0.01422 + 4 x 0.0236 + 0.1]+ 0.02/3 [0.1 + 4 x 0.22 + 2 x 0.343 + 4 x 0.91 + 4.6]

= 0.00938 + 0.06604

$= 0.07542$

$\therefore V_1 = F_{AO} * 0.07542$

$= 16652 * 0.07542$

$= 1256$ lit

$= 1.256\ m^3$

For MFR portion

$V_2/F_{AO} =(X_{out} – X_{in})/ (- r_{A)}$

$V_2/F_{AO} = (0.5 – 0) / 100$

$V_2 = 16652 \times (0.5 / 100)$

$= 83.3$ lit.

$\therefore$ Total volumre of reactor

$V = V_1 + V_2$

$= 1256 + 83.3$

$= 1340$ lit

$= 1.34\ m^3$

But volume $V = (\pi/4)* d^2l$

Where

'l' is length of reactor

And

'd' is diameter of reactor.

Let l = 3d

Thus $v = (\pi/4)* d^2 3d$

i.e. $d^3 = (1.34 \times 4) / (3 \times \pi)$

d = 0.828 m

And

L = 3d

= 3 x 0.828

= 2.486 m

Reactor Design By Heat Transfer Calculation

Since reaction is exothermic (maintained at 50^0C) Heat is evolved during the reaction. From energy balance heat liberated during the reaction.

Q = 94,281.1 KJ/hr

= 26.19 Kw

LMTD Calculation:

The streams flow in counter current fashion:

Calculation of hot fluid inlet temperature

T_{HI} = 0.512 x 44 + 0.488 x 23

= 33.75^0C

Let the cooling water enter the reactor at 23^0C

i.e. $T_{Ci} = 23^0C$

Assuming temperature raise of 10^0C

$\therefore T_{Co}$ = 23+10

= 33^0C

T_{Ci}	T_{Co}
23^0C	33^0C

T_{HO}	T_{HI}
50^0C	33.75^0C

LMTD = [(50-23) – (33.75-33)] / ln [(50-23)/(33.75-33)]

= 26.25 / 3.48

= 7.5^0C

Assuming $U_D = 80\ W/m^2\ {}^0C$

We have

$$Q = UA\,\Delta T_{LMTD}$$

$A = Q / UA\Delta T_{LMTD}$

$= 26.19 \times 10^3 / 80 \times 7.5 = 43.4\ m^2$

Choosing 5/8" OD, 16BWG

Let l, length of the tube = 2m

OD = 5/8" = 15.8 mm

ID = 0.495" = 12.54 mm

Heat transfer Area per unit tube length, a_t

$= 0.1636\ ft^2/ft$

$= 0.049 m^2/m$

Heat transfer area for 1 tube

$= 0.049 \times 2$

$= 0.1\ m^2/tube$

∴ No. of tubes = 289.

Nearest tube count P or S

274 tubes,

4-tube pass

1 shell pass

Shell ID = 438 mm = 17.25"

∴Corrected Heat Transfer area = 274.0.1

$= 27.4\ m^2$

Corrected overall coefficient

$= 26.19 / 27.74 \times 7.5$

$= 125\ w/m^{2\ 0}K$

Fluid velocities

a) Tube side (Cooling water):

Number of tube passes $N_p = 4$

Flow area available, a_t

$= (\pi/4)^* D^{2*} (N_T / N_P)$

$= (\pi/4) \times (12.54 \times 10^{-3})^2 (274/4)$

$= 0.0869\ m^2$

Tube side velocity

$V_t = m_t /(a_t \rho_t)$

Where

m_t = mass flow rate of water

= 1656 Kg/hr

ρt = Density of water

= 996 Kg/m^3

Tube side velocity = 1656 / 996 x 0.0869x 60 x60

= 0.519 > 0.5 m/s

Using square pitch of 13/16”

b) Shell side velocity:

Tube pitch, P_T = 13/16” x 0.0254

= 20.58 mm

S_m, cross flow area at center of shell = $[(P_T-D_o)L_S] D_s/P_t$

Where

(P_T-D_o)flow area between two adjacent tube rows:

Ds/P_T = Number of tube rows.

Ls = baffle spacing

= 0.2Ds = 0.0876 m

$S_m = [(20.58 – 15.8)10^{-3} \times 0.0876] \times [0.438 / (0.38 \times 10^{-3})]$

= 0.008 m^3

Velocity on shell side

$V_s = G_m/\rho s_m$

Where Gm is mass flow rate of mixed acid and chlorobenzene.

‘ρ’ is density or mixture containing acid mixture & chlorobenzene

And here ρ = 1300 Kg/m^3

∴Vs = (707.8 + 467.02) / (60 x 60 x 1.3 x 0.008)

= 0.313 m/s > 0.3 m/s

Summary:

Tube side velocity Vt = 0.519 m/s

ID of tube = 12.54 mm

OD of tube = 15.8 mm

Number of tubes = 274

Number of tube pass N_P = 4

IO of tube = 438 mm

No. of shell passes = 1

Shell side velocity = 0.313 m/s

Tube pitch (Square) = 20.58 mm

Corrected overall heat transfer coefficient U_d = 125 W/m^2 ^{0}K

Number of baffles N_b =(L/L_s)–1

= (2/0.0876) –1

= 22

25% Baffle cut, L_C = 0.25 D_s

= 0.25 x 0.438

= 0.1095 m.

Heat transfer coefficient on tube side

Properties of water evaluated at bulk temperature:

= (23 + 33) / 2 = 28^{0}C

Density of water = 998 Kg m^3

Viscosity, μ = 0.85 x 10^{-3} NS/m^2

Specific heat, Cp = 4187 J/Kg^{0}C

Thermal conductivity K = 0.6 w/m^{0}C

$N_{re} = V_t D_i \rho / \mu$

= (0.519 x 12.54 x 10^{-3} x 998) / (0.85 x 10^{-3})

= 7641

$N_{pr} = \mu Cp / K$

= (0.085 x 10^{-3} x 4187) / 0.6

= 6

From Perry chemical engineers hand book Fig. (10-10).

J_H = 0.8×10^{-3}

N_U = $J_H (Nre)^{0.8} (Npr)^{1/3}$

$H_i d_i/k = 0.8 \times 10^{-3} (7641)^{0.8}(6)^{1/3}$

Ho = $(0.8 \times 10 -3 (7641)^{0.8}(6)^{1/3} \times 0.6) / 12.5 \times 10^{-3}$

= 531 $W/m^2\ ^0c$

Heat transfer coefficient of shell side

Mass flow rate of mixed acid = 707.8 Kg / hr.

Molecular weight (M) of Mixed acid = 56.62 Kg/Kmol

Moles of mixed acid = 707.8 / 56.62

= 12.5 K mol

Mass flow rate of chlorobenzene

= 467.02 Kg/hr

Moles of chlorobenzene

= 467.02 / 112.5

= 4.1512 K mol

Moles of HNO_3 = 12.5 x 0.319 = 3.9875

Moles of H_2SO_4 = 12.5 x 0.3035 = 3.794

Moles of H_2O = 12.5 x 0.3775 = 4.71875

Moles C_6H_5Cl = 4.152

∴ total number of moles

= 3.9875 + 3.764 + 4.7187 + 4.152

= 16.8315

∴ % (Mole) of HNO_3 = 23.7%

% of H_2SO_4 = 22.5 %

% of H_2O = 22.8 %

% of C_6H_5Cl = 25.8 %

at temperature of 50^0c

Properties	HNO_3	H_2SO_4	H_2O	C_6H_5Cl
Mole fraction x_i	0.237	0.225	0.28	0.258
Viscosity $(\mu_I) NS/m^2$	1.35×10^{-3}	5.8×10^{-3}	0.62×10^{-3}	0.57×10^{-3}
Thermal conductivity $k_i (w/m^oc)$	0.46	0.42	0.638	0.245
Specific heat Cpi (j/Kg^oC)	1601.2	1507.1	4187	1381.7
Mol wt mi	63	98	18	112.5

Thermal conductivity of mixture,

$K_{mix} = \Sigma x_i K_i M_i^{1/3} / \Sigma x_i M_i^{1/3}$

$$\frac{(0.237 \times 0.46 \times 63^{1/3} + 0.225 \times 0.48 \times 98^{1/3} + 0.28 \times 0.638 \times 18^{1/3} + 0.258 \times 0.245 \times 112.5^{13}}{0.237 \times 63^{1/3} + 0.225 \times 98^{1/3} + 0.28 \times 18^{1/3} + 0.258 \times 112.5^{1/3}}$$

$= (0.433 + 0.497 + 0.468 + 0.305)/(0.94 + 1\ 0.73 + 1.24)$

$= 0.435\ W/m\ ^oC$

Viscosity of mixture

$\mu_{mix} = \Sigma x_i K_i M_i^{1/2} \mu / \Sigma x_i M_i^{1/2}$

$$= \frac{0.237 \times 1.35 \times 63^{1/2} + .225 \times 5.8 \times 98^{1/2} + 0.28 \times 0.62 \times 18^{1/2} + 0.258 \times 0.57 \times 112.5^{1/2}) 10^{-3}}{0.237 \times 63^{0.5} + 0.225 \times 98^{0..5} + 0.28 \times 18^{0..5} + 0.258 \times 112.5^{0..5}}$$

$[(2.539 + 12.918 + 0.736 + 1.6) 10^{-3}]/(1.881 + 2.227 + 1.187 + 2.736)$

$= 1.7 \times 10^{-3}\ NS/m^2$

Heat capacity of mixture

$C_{p\ mix} = \Sigma X_i . C_{pi} \mu_i^{1/3} / \Sigma X_i M_i^{\ 1/3}$

$= \underline{0.94 \times 1601.2 + 1 \times 1507.1 + 0.73 \times 4187 + 1381.7 \times 0.305}$

$0.94 + 1 + 0.73 + 1.24$

$= 1664$ J/Kg ^{0}K

∴**Properties of shell side fluid.**

Density, ρ = 1334 Kg/m^3

Specific heat C_p = 1664 J/Kg ^{0}K

Viscosity μ = 1.7×10^{-3} Pa-s

Thermal conductivity, k = 0.435 W/m ^{0}c

$N_{Re} = \rho\, v_s D_0/\mu$

$= 1334 \times 0.313 \times 15.8 \times 10^{-3}/1.7 \times 10^{-3}$

$= 4400$

$N_{pr} = \mu C_p/K$

$= 1664 \times 1.7 \times 10^{-3}/0.435$

$= 6.5$

$N_u = J_H (R_e)^{0.8}(P_r)^{1/3}$

J_H = 0.0067 from fig 10 –10,(Perry 6th edition)

$N_u = 0.007(4400)^{0.8} (6.5)^{1/3}$

$= 10.73$

$h_o d_o/R = 10.73$

$H_o = (10.73 \times 0.435)/15.8 \times 10^{-3}$

$= 297$ W/m^2 ^{0}C

$1/U_0 = (d_o/d_{i)} \times (1/h_i) + 1/h_0 + R_d$

where R_d is dirt coefficient = 2×10^{-3} m^2 ^{0}c/w

$\therefore 1/U_0 = 15.8 / 12.54 \times 1/531 + 1/297 + 2 \times 10^{-3}$

$= 2.3 \times 10^{-3} + 3.3 \times 10^{-3} + 2 \times 10^{-3}$

$= 135$ W/m^2 ^{0}C

Since U_0 calculated is higher than U_0 assumed design is valid in terms of heat transfer coefficient.

Pressure Drop calculation

Tube side:

Friction factor f

$= 0.079\ (N_{Re})^{-1/4}$

$= 0.079(7641)^{-0.25}$

$= 0.0085$

$\Delta P_L = (4fLVt^2/(2gdi))*(\rho_t.g)$

$= (4x0.0085x2x0.519^2 / (2 \text{ x } 12.54 \text{ x } 10^{-3})) \text{ x } 998$

$= 725\ N/m^2$

$\Delta P_t = 2.5 \text{ x } (998 \text{ x } 0.519^2) / 2$

$= 340\ N/m^2$

$= 4260\ N/m^2$

Shell side:

Pressure drop calculation By Bell's method:

Pressure drop at cross – flow zone,

$\Delta P_c = (bf_k w^2 Nc) /(\rho_t\ Sm^2)*(\mu_w/\mu_b)^{0.4}$

$b = 2 \text{ x } 10^{-3}$

$f_k = 0.15$

w = 707.8 + 467.02 / 60 x60 = 0.326 kg/s.

$N_c = D_s [1 – 2(l_c/D_s)] / P_T$

= 438 [1-2(109.5/438)] / 20.58

= 10.

$\Delta P_c = (2 \text{ x } 10^{-3} \text{ x } 0.15 \text{ x } 10 \text{ x } (0.326)^2)/ 1334 \text{ x } (0.008)^2$

$= 4 \text{ x } 10^{-3}\ KN/m^2$

Pressure drop at end zones

$\Delta P_l = \Delta P_c\ [1 + N_{cw}/N_c]$

$N_{cw} = 0.8l_c / P_p = 0.8 \text{ x } 109.5 / 20.58 \approx 4$

$\Delta P_l = 4 \text{ x } 10^{-3} [1 +4/16]$

$= 5 \text{ x } 10^{-3}\ KN/m^2$

Pressure Drop in window zone

$\Delta P_w = bw^2 (2+0.6\ N_{cw}) / (S_m.\ S_w.\ \rho)$

$b = \text{constant} = 5 \text{ x } 10^{-4}$

$S_w = S_{wg} - S_{wt}$

$S_{wt} = (Nt/8)* (1\text{-}Fc)\pi(d_0)^2 = (274 / 8)* (1\text{-}0.65)\ (15.8 \times 10^{-3})^2 \times \pi$

$= 0.0095\ m^2$

S_{wg} for 17.25” and $lc/D_s = 0.25$ is equal to $0.032\ m^2$

$\therefore\ S_w = 0.032 – 0.0095$

$= 0.0225\ m^2$

$\Delta P_w = 5 \times 10^{-4} \times (0.326)^2 \times (2 + 0.6 \times 4) / (0.008 \times 0.0225 \times 1334)$

$= 1 \times 10^{-3}\ KN / m^2$

$\therefore$ Total pressure drop,

$\Delta P_t = 2 \times \Delta P_l + (N_b – 1)\ \Delta P_c + N_b(\Delta P_w)$

$= 2 \times 5 + (22\text{-}1)\ 4 + 22 \times 1$

$= 10 + 84 + 22$

$= 102\ N/m^2$

$= 0.102$ K Pa

Pressure drop in both shell and tube are within the allowable limit.

$\therefore$ Design is valid in terms of pressure drop calculations also.

Volume of reactor in terms of heat transfer calculation = $\pi/4(d^2 l)$

$= \pi/4 \times 0.438^2 \times 2$

$= 0.3013\ m^3$

Since the volume calculated by reaction kinetics is greater than volume calculated by heat transfer calculation.

Therefore volume calculated by reaction kinetics is used for further calculation.

$\therefore$ Reactor volume $= 1.34\ m^3$

Total length of reactor = 2.48 m

Let 0.486m be the length of MFR portion

Then length of PFR portion = 2.486 – 0.486

= 2m

Diameter of the Reactor, d = 0.828

MECHANICAL DESIGN

a) Mechanical Design Of Reactor

STIRRER DESIGN

We use 6 blade turbine agitator .The diameter of impeller varies from 30 to 50 % of tank diameter.

Assuming that turbine operates at 200 rpm .

Diameter of reactor = 0.828 m

Diameter of impeller = 0.34 *0.828

= 0.28152 m

i.e using 34% of diameter of reactor as impeller diameter.

Density of mixed acid and chlorobenzene, ρ =1334 kg/m^3

Viscosity of mixture, μ = .0017 Pa-s

$\rho Nda^2/\mu = [1.334 \times 10^3 \times (200/60) \times (281.52/1000)^2]/(1.7 \times 10^{-2})$

` $= 20730 > 10,000$

From M.V. Joshi, Process Equipment Design, 2^{nd} edition

From power curve, N_p = 6.1 for Reynolds number greater than 10,000

From equation 14.1

Power, $P = N_P \rho\ N^3\ Da^5/(g_c \times 75)$

$= (6.1 \times 1.334 \times 10^3 \times (200/60)^{3)} x (281.5/1000)^5) / (9.81 \times 75)$

= 0.8 hp

Gland losses (10%) = 0.08 hp

Power input = 0.8 + 0.08 = 0.88hp

Transmission system losses (20%) = 0.88 x 0.2

= 0.176 hp

Total hp = 0.88+ 0.176= 1.056 hp

This will be taken as 2 hp to allow for fitting losses

∴It is advisable to use 3 to 5 hp motor.

Shaft design

Continuous average rated torque on the agitator shaft,

T_c= (hp x 75 x 60)/ (2 π N)

= (2x 75 x 60)/ (2 π x 200)

= 7.16 Kg m

Polar modulus of the shaft cross section is,

$Z_p = T_m/f_s$

Where T_m is maximum torque = 1.5Tc

f_s – shear stress – 400 kg/cm^2

Z_p =(1.5 x 7.16) /400

= 2.685 cm^3

$\pi d^3/16 = 2.685$

d = 2.5 cm

Torque T_m is resisted by force F_m acting at a radius of 0.75R_b From the axis of agitator shaft.

Where R_b is radius of blade.

. Force, $F_m = T_m/0.75R_b$

F_m = (1.5 x 7.16x 100) / (0.75 x 14.06)

= 102 Kg

Maximum bending momentum

$M = F_m \times l$

Where 'l' is length of overhang of agitator shaft between bearing and agitator.

Let ‘l’= 1500mm

∴M = 102 x 1.5

= 153Kg-m

Equivalent bending moment

$$M_e = \frac{1}{2}\left[M + \sqrt{M^2 + T_m^{\ 2}}\ \right]$$

$$= \frac{1}{2}\left[153 + \sqrt{153^2 + 10.74^2}\right]$$

= 306 Kg .m

The stress due to equivalent bending

F = M_c/Z

Z = π$(2.5)^3$/32 (Modulus of section of the shaft cross section)

Z = 1.533 cm^3

∴f = (306*100)/1.533

= 19948kg/cm^2

Stress f is higher than the permissible elastic limit (2560 Kg/Cm^2). Therefore use a 5 cm diameter shaft for which the stress will be,

f = 2480 Kg/cm^2

Deflection of shaft

$\delta = (Wl^{3)}/(3\ EI)$ [W = F_m]

Where E is the modulus of elasticity = $19.5*10^5$ Kg/cm^2

$\therefore \delta = [102(150)^3\ ]/[3 \times 19.5 \times 10^5 \times (\pi \times 5^4)/64]$

= 1.91cm

Critical speed , N_c = (4.987 x 60) /√δ

= 216rpm

Since actual shaft speed is 200 rpm which is 92% of the critical speed. Therefore it is necessary to increase the value of critical speed by decreasing the deflection.

Choose therefore 6cm diameter shaft.

Then,

δ = 0.92 cm

And N_c = 60 x 4.987/ 0.92 = 324 rpm

Actual speed is 61% of the critical speed

Blade design

Using blade width, W = 75mm

Blade thickness, t = 8mm

Number of blades = 6

Stress in the blade, F =(maximum torque)/(tw^2/n)

=(10.74*10)/(0.8 x 7.5^2/6)

= 143 Kg/cm^2

The value of stress is well within the limit for carbon steel.

Hub and key design

Hub diameter of agitator = 2 x shaft diameter

= 2*6

= 12 cm

Length of the hub = 1.5 x shaft diameter= 9 cm

Length of key = 1.5 x shaft diameter = 9 cm

T_{max}/(d/2)= lbf_s = (lt/2)f_c = (10.74 x 100)/(6/2)

f_s- shear stress in key (for carbon steel it is = 650 kg/cm^2)

f_c – stress in crushing of key(for carbon steel it is = 1300 kg/cm^2)

9 x b x 650 = 9 x t/2 x 1300 = 358

on solving,

b = 6 mm

t = 6 mm

Use 6mm x 6mm x 9 cm key

Stuffing box and gland

Internal pressure = $1.1*10^5$ Pa

= 1.2 kg/cm^2

Internal diameter of stuffing box (in cm)

$B = d+\sqrt{d}$

$= 6 + \sqrt{6} = 8.44cm$

Thickness of stuffing box in mm, t = Pb/2f + C

Permissible stress in the material of stuffing box, ‘f’ = 950 kg/ cm^2

t = (1.12 x 8.4 x 10) /(2 x 950) + 6

= 6.05mm

Load on gland,

$F = (\pi/4)\ p(b^2 – d^2)$

$= (\pi/4)(8.44^2 – 6^2)1.12$

= 31 Kg

Size of the stud

$F = (\pi d_0^2/4)\ nf$

n is the no of studs = 4

f is the permissible stress for stud = 587 Kg/cm^2

d_0^2 = 0.0144 cm

d_0 = 0.12mm

But minimum stud diameter of 15 mm should be provided.

∴Stud diameter = 15 mm

Flange thickness = 1.75 x d

= 1.75*15=27mm

<u>Coupling: -</u>

A clamp coupling of cast iron is used

Force per bolt = 2 $T_{max}/(\pi\mu dx\ (n/2))$

No of bolts, n= 8 (for shaft diameter of greater than 5cm)

μ - Coefficient of friction = 0.25

Force per bolt= (2 x 10.77 x 100) / (π x 0.25 x 6 x (8/2))

= 114 kg

Area of bolt = (force on bolt)/(shear stress on bolt)

=789.7/587

= $0.19 cm^2$

Diameter of bolt=(0.19 x 4)/Π

=0.24cm

Overall diameter of coupling= 2x shaft diameter

= 2*6

= 12cm

Thickness of reactor vessel

Allowable stress value, f = 1130 kg/cm^2 (upto 150^0 C for carbon steel)

Thickness of reactor, t = (P* D)/[(2*f*j)-P] + C

Where

'j' is joint efficiency = 0.85

'P' is the design pressure

P = 1.1 P_{actual}

= 1.1*1.05

= 1.156 kg/cm^2

∴t = (1.156*82.8)/[(2*1130*0.85)-1.156] + 3

= 4mm with corrosion allowance

Design of reactor head

Using Flat head

Thickness of head,t = (CD)/10*(√(P/f))

Where 'C' is taken as 0.5

(from table 3.27, IS 2825 – 1969)

$\therefore$ t =(0.5*828)/10*((1.156*100)/(1130))$^{0.5}$

=13 mm

=15 mm with 2mm allowance for corrosion.

Conical bottom thickness

T_h =PD /(2*f* J*(cosα)

Where

$\alpha = 60^0 / 2$

$= 30^0$

$\therefore T_h$ = 1.156 x 82.8 / (2 x 1130 x 0.85xcos30) + C

= 0.8 + 3

= 3.8 mm with corrosion allowance.

Nozzle diameter for chlorobenzene inlet

Feed rate of chlorobenzene

= 467.02 Kg/hr.

= 0.130 Kg/s

Assuming velocity, v_1 = 0.01 m/s

Area of nozzle = m_t /(v_1 x $\rho_{1)}$

Where m_t is mass flow rate of chlorobenzene.

V_1 is the velocity of chlorobenzene

ρ_1 is density of chlrorobenzene = 890 kg/m^3

$\therefore$ Area of the nozzle = 0.129 /(0.01 x 890)

= 0.017m^2

Diameter of Nozzle = [(0.0177 x 4) / π]$^{0.5}$

D_n = 17 cm(using diameter of 45 cm)

Thickness of the nozzle

$T_h = PD_n / (2Fj\text{-}P)$

= 45 x 1.156 /[(2 x 0.85 x 1130) – 1.156]

= 0.25 + 3 mm

= 3.25 mm

Nitrating acid mixture inlet nozzle Diameter:

Mass flow rate of acid mixture:

Mt = 0.196 Kg/s

Velocity, v_1 = 0.01 m/s assuming

Density of mixture, ρ= 1300 Kg/m^3

$\therefore$ Area of nozzle = $m_t / \rho \, x v_1$

= 0.196 / 1300 x 0.01

= 0.15 m^2

Diameter of nozzle = $\sqrt{0.017 \times 4 / \pi}$

= 14 cm(using nozzle diameter of 40cm)

Thickness of the nozzle

$T_h = PD_w / (2fJ\text{-}P) + C$

=1.156 x 40 / (2 x 0.85 x 1130 – 1.156) + C

= 0.2 + 3

= 3.2 mm

Nozzle diameter for cooling water inlet and outlet

Mass flow rate of water = 1656.54 Kg/hr

= 0.46 Kg/s

Area of nozzle = Mass flow rate / velocity x density

= 0.46 / 0.01 x 998

$= 0.046\ m^2$

Diameter of nozzle = $\sqrt{0.046 \times 4 / \pi}$

= 24 cm(using 35 cm nozzle diameter)

Thickness of nozzle

$Th = P_D D_N / 2fJ - P_0 + C$

= 1.156 x 35 /[(2 x 1130 x 0.85) – 1.156]

= 1.8 + 3

= 4.8 mm.

Support Design

Bracket or lug support for a reactor:

Diameter of reactor = 0.828 m

Height of reactor = 2.486 m

Clearance from vessel bottom to foundation = 0.5 m (assuming)

Wind pressure = 128.5 kg/cm^2 (assuming)

Number of Brackets to be provided for reactor of diameter 0.828 m = 2 numbers.

Diameter of anchor belt circle

(from table 13.2, M.V. Joshi, 2nd edition) = 0.95 m

Height of bracket from foundation = 1.8 m (assuming)

Permissible stresses for structural steel

(Is – 800) Tension = 1400 Kg / cm^2

Compression = 1238 Kg/cm^2

Bending = 1575 Kg/cm^2

Permissible bearing pressure for concrete = 35 Kg/cm^2

Calculation of weight of reactor vessel with its content:

Length of reactor = 2.486 m

Outside diameter of reactor = 0.832 m

Inner diameter of reactor = 0.828 m

Density of structure steel = 7800 kg/m^3

Weight of reactor vessel,

$W_1 = 7880 \times \pi/4\ 90.832^2 – 0.828^2) \times 2.486$

$= 77$ Kg.

Weight of chlorobenzene + Mixed acid,

$W_2 = \pi/4\ (D^2{}_0 – D_i^2)\ l \times \rho$

$= \pi/4(0.832^2 – 0.828^2) \times 2.486 \times 1334$

$= 1175$ Kg

Weight of the tubes

$W_3 = N_t \times \pi/4\ (d_0^2 – d_i^2)\ l \times \rho$

$= 274 \times \pi/4\ (15.8^2 – 12.54^2)10^{-6} \times 2.486 \times 7880$

$= 313$ Kg.

Weight of the head

$W_4 = t \times l \times b \times \rho$

$= 15 \times 10^{-3} \times 828 \times 10^{-3} \times 828 \times 10^{-3} \times 7880$

$= 81$ Kg

Weight of 4 nozzles

$W_5 = 100$ Kg.

$\therefore$ Total weight $W = w_1 + w_2 + w_3 + w_4 + w_5$

$= 1746$ Kg

Design weight = 1.3 x 1746

= 2270 Kg.

Load due to wind pressure

Wind pressure, Pw = kph.Do.

k-Coefficient depending on the shape factor = 0.7

'h' is the height of reactor vessel = 2.486

'p' is given wind pressure =128.5kg/cm^2

'Do' is the outside diameter of vessel

$\therefore$Pw=0.7x128.5x2.486x0.832 = 186 Kg.

Maximum total compressive load in the support is

P= $\frac{4Pw(H-F)}{NDb}+\frac{\varepsilon w}{n}$

H – Height of the vessel above the foundation

F – Vessel clearance from foundation to vessel bottom.

$\sum$W – Maximum weight of the vessel

n = number of brackets

$$P = \frac{4x186(2.986-0.5)}{2x0.95}+\frac{2270}{2}$$

= 2109kg

Bracket:

(a)Base plate:

Suitable base plate size, a = 140 mm

B = 150 mm

Average pressure on the plate, P_{av} = P/(aB)

P_{av}= (2109)/(14x15)

=10.042 Kg/cm^2

Maximum stress in a rectangular plate subjected to a pressure P_{av} and fixed at the edges is given by

$$f = 0.7P_{AV}\frac{B^2}{T^2}\left(\frac{a^2}{B^2 + a^2}\right)$$

$$= 0.7x10.042x\frac{15^2}{T^2}\left(\frac{14^2}{15^2 + 14^2}\right)$$

$$= \frac{736}{T^2}$$

$$f = 1575Kg/cm^2$$

For structural steel value of 'f' =1575 kg/cm^2

$\therefore T_1^2$ = 736/1575

$\therefore T_1$ = 7 mm

$\therefore$Using 7 mm thick plate.

(b) Web plate.

Bending moment of each plate =

$$\frac{P}{2}\frac{(D_{im} - D)}{2}x100$$

$$= \frac{(2109)(0.95 - 0.832}{4}$$

$$= 6433kg.cm$$

Stress at the edge, f = (bending moment of each plate)/(T_2*a*a*0.707)

Where T_2 is web plate thickness

$$\therefore f = \frac{6433}{T_2 x 14 x 14} x \frac{1}{0.707}$$

$= 46.42/T_2$

f = 1575 kg/cm^2 for structural steel

Therefore T_2 = 46.42/1575

= 3mm

Column support for bracket:

It is proposed to use a channel section as column.

The size chosen is ISMC 150.

Size – 150 x 75

Area of cross section – 20 .88 cm^2

Modulus of section, z – 19.4 cm^3

Radius of gyration, r – 2.21 cm

Weight – 16.4 Kg/m

Height from foundation 'l'- 1.8m

Equivalent length for fixed ends l_e=1/2

= 1.8/2

f = 0.9 m

Slenderness ratio = l_e/r

Slenderness ratio $= \frac{0.9x100}{2.21} = 40$

For the load acting eccentric on a short column, the maximum combined bending and direct stress is given by,

$$f = \frac{\sum W}{An} + \frac{\sum We}{nz}$$

$\sum$w = Load on column

A – area of cross section

e – eccentricity

z – modulus of section of cross – section

n – number of columns = 1

$$f = \frac{2109}{20.88x1} + \frac{2109x7.5}{1x19.4}$$

$$= 916Kg / cm,^{2}$$

The calculated value of ‘f’ is less than the permissible compressive stress and hence the Channel selected is correct.

Base plate for column:

Size of the column 150 x 75

It is assumed that the base plate extends 25 mm on either side of channel

Side B – 0.8 x 75 + 2 x 25=110mm

Side C – 0.95 x 150 + 2 x 25 = 192.5 mm

Bearing pressure, Pb = (p/4)*(1/(B*C))

= (2109/4) x (1/(11x19.25))

= 2.48 K/cm^2

This is less than the permissible bearing pressure for concrete.

Stress is the plate, f= $\left[\frac{\frac{Pb}{2} x \frac{\overline{h^{2}}}{10}}{\frac{t^{2}}{6}} \right]$

f = (6*2.48*2.5^2)/(2t^2)

but f = 1575 Kg/cm^2

$\therefore\ t^2 = 46.45/1575$

and 't' =1.7mm

But it is usual to select a plate 4 to 6 mm thick.

MINOR EQUIPMENT DESIGN

CONDENSER

Recycle to the still from material balance, R = 0.451

∴ Total feed to the still = 1.451

Composition p - nitrochlorobenzene coming out of first crystallizer

from material balance = 0.4815.

Composition of 0-nitrochlorobenzene = 0.5185

Composition of p = nitrochlorobenzene coming out of second crystallizer = 0.38.

Composition of 0 – nitrochlorobenzene coming out of second crystallizer = 0.62

∴ Feed composition to the still

$$x_F = 1 \text{ x } 0.4815 + 0.451 \text{ x } 0.38 / 1 + 0.451$$

$$= 45\%$$

Therefore distillate

$$D = (1 \text{ x } 0.4815 + 0.451 \text{ x } 0.38) / 0.7$$

$$= 0.9327 \text{ Kg}$$

Residue contains only 0- nitrochlorobenzene

Reflux ratio

$$R= L / D$$

$$G = (L + D) = (R +1) D$$

Reflux ratio from graph of composition of p-nitrochlorobenzene in vapour phase vs compositions of p – nitrochlorobenzene in liquid phase is equal to 6.

$$\therefore (L + D) = (6 \text{ x } 1.2 + 1) D$$

Kg's of mononitrochlorobenzene formed in a Reactor = 641.01 Kg/hr

Out of which 65% is p – Isomer and 35% is 0-Isomer (Neglecting m – Isomer)

Feed to still after the crystallization in 1^{st} crystallizer = 641.01 x 0.65 x 0.5 / 0.4815

= 432.67 Kg.

For 1 kg of Mother liquor from crystallizer 1, D = 0.9327 Kg.

∴For 432.67 Kg. Of feed,

$$D = 432.6 \text{ x } 0.9327$$

$$= 403.55 \text{ Kg/hr.}$$

∴ feed to the condenser

= (R+1)D

= (6 x 1.2 + 1) 403.55

= 3309 Kg/hr.

= 0.919 Kg/s

Latent heat of p – nitrochlorobenzene at a temperature of 214.541^0C

$= (5.3x10^7)/(157.5x1000)$

= 336.5 kj/kg

Latent heat of 0-Nitrochlorobenzene at a temperature of 241.541^0C

$= 5.38 \times 10^7 / 157.5 \times 1000$

= 341.6 KJ/Kg

Latent heat of mixture of para and ortho Isomer

= 0/7 x 336.5 + 0.3 x 341.6

= 338 .03 Kj / Kg

∴Heat content of para and ortho isomer mixture fed to the condenser;

$$Q = m\lambda$$

Where

'm' is mass flow rate = 0.910 KJ/sec

∴Q = 0.919 x 338.03

= 310.65

Let cooling water comes at temperature = 30^0C

Assuming raise of cooling water temperature to be 10^0C

Amount of cooling water needed

$$Q = m_w C_p \Delta t$$

$$310.65 \times 10^3 = m_w \times 4.18 \times 103 \ (40\text{-}30)$$

$$m_w = 7.43 \text{ Kg/sec.}$$

$$\Delta t_{LMTD} = [(214.54 - 30) - (214.54 - 40)] / \ln[(214.54 - 30) / (214.54 - 40)]$$

$$= 10 / 0.055$$

$$= 179.5^0C$$

Assuming $U_d = 250 W/m^2K$

Area, $A = Q / U\Delta t_{LMTD}$

= 310650 / 250 x 179.5

= 70 m^2

Choosing tube of outer diameter = 0.75" = 19.65 mm, 16BWG

Inner diameter = 0.620 = 15.74 mm

Length, l = 2.5m

Heat transfer area/unit tube length,

a_t = 0.1963ft^2/ft

= 0.059m^2/m

∴Heat transfer area for 1 Tube

= 0.059 x 2.5

= 0.147 m^2/Tube

Number of tubes = 70/0.147

=476 tube

Choosing tube count of 432 for 1 shell and 4 tube pass and shell diameter of 635 mm.

(1 inch triangular pitch)

∴Corrected heat transfer area = 448 x 0.147

= 66.0 m^2

∴Corrected Ud = 262 W/m^2 ^{0}K

Film transfer coefficient:

Temperature of wall,

T_w = ½ [214.541 + ((30+40))/2]

= 124.77^{0}C

Film temperature ,

T_f = (124.77 + 214.541) / 2

= 169.6^{0}C

Properties of p – Nitrochlorobenzene at 169.6^{0}C

Density ρ_L = 1120 Kg/m^3

Viscosity μ = 0.38 x 10^{-3} Pa –s

Specific heat Cp = 1146 J/Kg^{0}C

Thermal conductivity K = 0.113 Wm^{0}K

Properties of mixture of ortho and para Isomer

ρL = 0.7 x 1250 + 0.3 x 1210

= 1238 Kg/m3

μ = 0.4 x 10^{-3} Pa-s

Cp = 1146 KJ / Kg^{0}K

Thermal conductivity, K = 0.112 x 0.7 + 0.113 x 0.3

= 0.1123 W/m^{0}K

Shell side heat transfer coefficient

$R_e = 4/\mu\ (W/(N_{t\pi}\pi D_0))$

Where

'w' is mass flowrate of mixture = 0.99 Kg/s

Number of Tubes N_t = 432.

Outside diameter of tube D_o = 15.8 mm

Viscosity, $\mu = 0.38 \times 10^{-3}$ Pa-s

$Re = 4/0.38 \times 10^{-3}\ (0.991 / 448 \times \pi \times 19.6 \times 10^{-3})$

= 491

Choosing horizontal tube condensor

$h_0=1.51\ (K^3\rho^2\ g / \mu^2)^{0.33}\ (Re)^{-0.33}$

$= 1.51[\ (0.1123^3 \times 1140^2 \times 9.8) / (0.38 \times 10^{-3})^2\ ]*(491)^{-0.33}$

$h_0 = 448$ W/m^2 ^{0}K

Tube side transfer coefficient : (cooling water)

Flow area = 0.3014 in^2

$= 194 \times 10^{-6}$ m^2

flow area per pass = $448 \times 194 \times 10^{-6} / 4$

= 0.021 m^2 / pass

G_t = 7.43 / 0.021 = 554 Kg/m^{2}s

At average temperature of water at 35^{0}C properties are

ρ = 1000 Kg/m^3

$\mu = 1 \times 10^{-3}$ Pa -s^s

C_p = 4.187 KJ / Kg^{0}K

K = 0.578 W/m^{0}K

$R_e = G_t\ D_i / \mu$

$= 544 \times 15.94 \times 10^{-3} / 1 \times 10^{-3}$

= 8562.5

$(N_{pr})\ = \mu c_p /K = 7.2$

$h_i d_i / k = 0.023 (Re)^{0.8} (Pr)^{0.3}$

$= 0.023(8562.5)^{0.8}(7.2)^{0.3}$

$=50.24$

$h_i=50.24 \times 0.578 / 15.74 \times 10^{-3}$

$= 1810 W/m^2K$

∴Overall heat transfer coefficient

$$1/u_{od} = D_0/D_i(1/h_i)+1/h_0+R_d$$

R_d is the dirt coefficient factor

$$= 3 \times 10^{-4} m^2 \, ^0C/w$$

$1/u_{od} = 19.65 / 15.74 (1/1810) + 1/448 + 3 \times 10^{-4}$

$= 3.22 \times 10^{-3}$

$\therefore u_{0d} = 310 W/m^2 \, ^0K$

Calculated value of u_{0d} is greater than assumed value hence design is valid in terms of heat transfer coefficient.

Pressure drop calculation:

Properties of p – nitrochlorobenzene vapour at temperature 214.541^0C

$\mu = 1.12 \times 10^{-5}$ Pa-S

K = 0.019 W/mk

Cp = 1.206 Kj/Kg^0K

Properties of 0-Nitrochlorobenzene vapour at temperature 214.541^0C

$\mu = 1.07 \times 10^{-5}$ Pa-S

K = 1.1206 KJ/Kg^0K

Cp = 0.016 w/mK

Density of Mixture ≈ P/RT

$= 47996.051 / 8.314 \times 487.541$

$= 11.84 Kg/m^3$

Flow area a_s = (shell ID) / P_T C'B.

C' = clearance between tubes.

P_T = 25.4 mm

Shell ID = 635 mm

$C' = P_T – D_0$

$= 25.4 – 19.65$

$= 5.75$ mm

B = Baffle spacing

$\therefore a_S=(0.635)\ (5.75 \times 10^{-3}) / 25.4 \times 10^{-3} \times 0.635$

$= 0.091\ m^2$

Hydrolic diameter

$= 4\{[(P_T /2) \times 0.86\ P_T – ½ \times \pi/4 \times D^2{}_0]\ \}/ (\pi D_0/2)$

$= 4[25.4/2 \times 0.86 \times 25.4 – (½\ \pi \times 19.65^{2)}\ /4]\ /(\pi \times 19.65 /2)$

$= 4[277.41 – 151.63]/30.86$

$= 16.3$ mm

$G_s = 0.991 / 0.091 = 10.89\ Kg/m^2s$

$(N_{Re}) = 10.89 \times 16.3 \times 10\text{-}3 / 0.01095 \times 10^{-3})$

$= 16210$

Friction factor,

$f = 1.87\ (Re)^{-0.2}$

$= 1.87(16210)^{-0.2}$

$= 0.269$

$N_b+1 = L/D_s$

$= 2.5 / 0.635$

$N_b+1 = 4$

$\therefore$ number of baffles, $N_b = 3$

$\rho_{vap} = 11.84\ Kg/m^3$

$\Delta Ps = [\ (4f(N_b+1)D_sG_s^2g\ )/(\ 2gD_e\rho_{vap}\ )]\ \ x\ (1+0/2)$

$= [4 \times 0.269\ (4)\ 0.635 \times 10.89^2 \times 9.8\ ]/\ [23 \times 9.8 \times 16.3 \times 10^{-3} \times 11.84]\}\ 0.5$

$= 421.2\ N/m^2$

Tube side pressure drop

$(N_{Re})_t = 8562$

$f = 0.079\ (8562)^{-0.25}$

$= 0.0082$

$\Delta P_L=[4fLv_t^2/2gD_i\ ] \times g\rho$

$= 2fLG_t^2/\rho D_i$

$=[2 \times 0.0082 \times 2.5 \times 554^2]/[1000 \times 0.01575]$

$= 801\ N/m^2$

$\Delta P_t = 2.5\ Gt^2 / 2 \times \rho$

$= [2.5 \times 554^2]/[2 \times 1000]$

$= 383.(4N)m^2$

$\therefore (\Delta P)$ total = 4 (801 + 383.64)

$= 4738.58\ N/m^2$

Pressure drop calculated for both tube side and shell side are within the limit.

$\therefore$ Design is valid.

Mechanical Design of condenser

Inner diameter of shell = 635 mm

Length of the shell = 2500 mm

Pressure inside the condenser = 47.36 Kpa

Pressure outside the condenser = 101.3 Kpa

Pressure exerted on the condenser = 53.63 Kpa

$=0.53\ Kgf/cm^2$

From IS 2825 – 1969, page no – 180

For cylindrical shell

$L/D_0 = 2.5/(0.635+2t)$

Where ‘t’ is the thickness of shell

Assuming ‘t’ = 4mm

Step 1:

L/D_0 = 2.5/(0.635+2*4)

= 3.88

Step 2 :

D_0/t = 635/4

= 158.75:

From figure 2 for carbon and low alloy steel,

Factor A = 0.0001

Factor B = 1800

Factors ‘A’ and ‘B’ are obtained from the chart for shell thickness for vessel under external pressure.

Therefore working pressure, p_a == B /(14.22*(D_0/t))

= 1800/(14.22*158.75)

= 0.797 Kgf/cm^2

Since working pressure is greater than external pressure, thickness chosen is correct.

Head thickness:

Using shallow dished & torispherical head

$$t_h = \frac{PRcW}{200fJ}$$

Rc – crown radius

W – stress intensification factor

$$W = 1/4\left[\sqrt{\frac{Rc}{Rk}}\right]$$

$$Rk = 6\% Rc$$

$$W = 1/4\left[3 + \sqrt{\frac{1}{0.06}}\right]$$

$$J = 0.85$$

$$t_h = \frac{0.11 * 1.77 * 643}{0.85 * 200 * 95}$$

$$= 4.7 mm$$

From IS 4503 – 1967

Minimum thickness to be used = 10mm, including the corrosion allowance

Transeverse buffles:

Baffle spacing = Inner diameter of the shell

= 635 mm = D_S

Number of baffles,

$N_b + 1 = L/D_S$

$= 2.5/0.635$

$= 4$

$\therefore N_b = 3$

Thickness of baffles = 6 mm (From IS 4503 –1967)

Tie rods:

Tie rods are provided to retain all the baffles and the support plates accurately in position and shall be of same material as that of baffles.

From IS 4503 –1967

Diameter of tie rod = 10 mm

Number of tie rods = 6

Flanges:

Design pressure = 0.11 MN / m^2

Shell thickness = 4 mm

Flange material – IS: 2004 – 1962 class 2

Gasket material – asbestos composition

Bolting steel = 5% Cr Mo steel

Allowable stress of flange material – 100 MN / m^2

Allowable stress of bolting material – 138 MN/m^2

Inside diameter of shell = 635mm

Outside diameter of shell = B = 643mm

Determination of gasket width

$$\frac{do}{di} = \left[\frac{y - pm}{y - p(m+1)}\right]0.5$$

m – gasket factor – 2.75

y – min design seating stress – 25.5 MN/m^2

$$\frac{do}{di} = \left[\frac{25.5 - 0.11x2.75}{25.5 - 0.11(2.75+1)}\right]^{1\frac{1}{2}}$$

$$= 1.002$$

Let diameter of the gasket equal to 653 mm,

i.e, 10 mm greater than shell diameter.

do = 0.653 x 1.002

= 0.6543m

$$Meangasketwidth = \frac{0.6543 - 0.653}{2}$$

= 6.5 x 10^{-4} m

Taking gasket width of 11 mm, Let diameter of the gasket equal to 653 mm, i.e, 10 mm greater than shell diameter Gasket thickness = 1.6 mm

Therefore do = 0.675 m

Basic gasket seating width b_0 = (gasket width)/2

= (0.011)/2 = 5.5 mm

Diameter of location of gasket load reaction is,

G = di+N

= 0.635+0.011

= 0.646m

Estimation of bolt loads:

Load due to design pressure:

$$H = \frac{\pi G^2 P}{4} = \frac{\pi (0.646)^2 x 0.11}{4}$$

= 0.016 MN

Load to keep joint tight under operation

Hp = πG $(2b_0)$mp

=πX0.646x2x5.5x10^{-3}x2.75x0.11

= 3.07x10^{-3} MN

Total operating load, Wo = H+Hp

=0.016 +3.07x10^{-3} MN

=0.02 MN

Load to seat gasket under bolting up condition

Wg = πG b_0y

= π x 0.646 x 0.0055 x 25.5

= 0.285 MN

Since the load to seat gasket is greater than to load under operation.

∴ Controlling load is load to seat gasket, which is = 0.285 MN

Calculation of minimum bolting area,

$$Am = Wg/Sg$$

Where

Sg is the allowable stress in the bolting material which is equal to 138 MN/m^2.

$$\therefore \quad Am = 0.285/138$$

$$= 0.00206 \ m^2.$$

The total number of bolts may be approximately equal to the mean diameter of gasket in centimeters divided by 2.5 and should be multiples of 4.

Therefore number of bolts = 646/(10*2.5)

= 25.84

= 28 bolts

Calculation of diameter of bolt

Am = A*Number of bolts

Where A is area of single bolt.

$$Am = ((\pi d^2)/4)*28$$

$$0.0026 = ((\pi d^2)/4)*28$$

$$\therefore d = 0.00967 \text{ m}$$

$$= 1 \text{ cm}$$

Bolt size – M 18 x 2

Pitch diameter = 16.376 mm

Minor axis = 14.48 mm

Actual bolts area $= 28*\pi/4(16.375^2 + 14.48^2)/2$

$= 52 \text{ cm}^2$

Pitch of the bolt is actually 3.5 to 5 times the diameter of the bolt.

Let pitch of the bolt = 4.75*d

= 4.75*18

=85.6 mm

Pitch circle diameter B = $(85.6*28)/\pi$

= 762mm

Or

B = (Outside diameter of gasket +2 *diameter of the bolt +12mm)

= 646 +2*18 +12

= 694m

Outside diameter of flange = (B +2*d)

= 694 +2*18

= 730 mm

Calculation of flange thickness

$$T_f = G\sqrt{\frac{P}{fk}} + C$$

Where

'P' is the design pressure

'G' is the mean gasket diameter

'f' is permissible stress

'C' is corrosion allowance

$$k = \frac{1}{\left[0.3 + \frac{1.5 W_m h_G}{HG}\right]}$$

'W_m' is the total bolt load

'h_G' is the radial distance from gasket reaction to bolt circle

Which is = (B-G)/2

'H' is the total hydrostatic end force, = $\pi/4(G^2P)$

$$k = \frac{1}{0.3 + \frac{1.5 \times \frac{0.02\times10^6}{98} \times \frac{(730-646)}{2}}{\frac{\pi}{4}\times(0.646)^2 \times \frac{0.05\times10^6}{9.8} \times 646}}$$

$$= \frac{1}{0.3 + (128571)/1080267}$$

= 1/(0.3+0.119)

= 2.38

$\therefore t_f = 646\times\sqrt{\frac{0.05}{2.38\times138}}+C$

$= 8 + 4$

$= 12mm$

Tube sheet thickness

$$t_{ts} = FG\sqrt{\frac{P}{f}}$$

$$= 0.75x0.646\sqrt{\frac{0.055}{95}}$$

$$= 11.1mm$$

T_{ts} = 14 mm including corrosion allowance

Channel and channel cover:

$t_h = G_c\sqrt{\frac{KP}{f}}$

$= 0.646\sqrt{\frac{0.33x0.055}{95}} + C$

=8mm +3mm

=11mm

Saddle Support:

Material- low carbon steel

Diameter of vessel= 643 mm

Length of the shell, L = 2.5m

Knuckle radius = 6% of diameter

= 38.58mm

Total depth of head =

$$\sqrt{\frac{D_o r_o}{2}}$$

$$= \sqrt{\frac{643x38.52}{2}}$$

$$H = 111.3mm$$

Weight of vessel & its contents.

1) Weight of shell

Density of carbon steel = 7880 Kg/m^3

Outer diameter of vessel= 643 mm

Inner diameter of vessel= 635 mm

Length of the shell, L = 2.5m

$\therefore$W1 = 2.5*7880*(π/4)*[$0.643^2 - 0.635^2$]

=156.58 Kg

2) Weight of the tubes

Outer diameter of tubes= 19.65 mm

Inner diameter of tubes= 15.74 mm

Length of the shell, L = 2.5m

Number of tubes = 432

$\therefore$Weight of tubes ,W2 = 2.5*7880*432*(π/4)*[$0.01965^2 - 0.01574^2$]

= 924Kg

3) Weight of the tube sheets

Diameter of tube sheet= 635 mm

Thickness of tube sheet =14 mm

Weight of tube sheet, W3 =0.0015*2*7880*(π/4)*[0.635^2]

=74 Kg

4) Weight of tie rods

No. of tie rods = 4

Diameter of tie rod = 10 mm

Weight of tie rods W4= 4*2.5*7880*(π/4)*[0.01^2]

= 6.2 Kg.

5) Weight of baffles

No of baffles =3

Thickness of baffle = 6 mm

Weight of the baffle = 3*0.006*7880*(π/4)*[0.635^2]

W5 = 25 Kg.

6) Weight of the liquid

Tube side

W6 =2.5*900*432*(π/4)*[0.01965^2 –0.01574^2]

= 114 Kg.

Shell side

W7 = 2.5*1238*(π/4)*[0.635^2]

= 980 Kg.

∴Total weight of vessel with its content

W = W1 + W2 + W3 + W4 + W5 + W6 + W7

=2280 Kg.

Distance of saddle center line from shell end,

A = 0.5 * R

= 0.5 *(643/2)

= 160.75 mm

The bending moment at the support is

$$M1 = QA\left[1 - \frac{1 - \frac{A}{L} + \frac{R^2 - H^2}{2AL}}{1 + \frac{4}{3}\cdot\frac{H}{L}}\right]$$

If two symmetrical supports are considered then each support will carry a load equal to ‘Q’

Here

‘R’is the crown radius

‘L’ is the length of shell

$$Q = \frac{w}{2}(L + \frac{4}{3}H)$$

$$= \frac{2280}{2}\left[2.5 + \frac{4}{3}x0.1113\right]$$

$$= 3019Kg$$

$$M_2 = \frac{QL}{4}\left[\frac{1 + 2\left(\frac{R^2 - H^2}{L^2}\right)}{1 + \left(\frac{4}{3}\right)\left(\frac{H}{L}\right)} - \frac{4A}{L}\right]$$

$$M_1 = 404Kg.m$$

$$M_2 = 1348Kg.m$$

Stress due to the bending at the topmost fiber of the crossection is given by

.

$$f_1 = \frac{M_1}{k_1 \pi R^2 t} \quad k_1 = 1$$

t= thickness of the shell

$$f1 = \frac{404}{\pi x 0.004 x 0.321^2}$$

$$= 31.20 kg / cm^2$$

Stress due to the bending at the bottommost fibre of the crossection is given by

$$f_2 = \frac{M_2}{k_2 \pi R^2 t}$$

K_2=1

f_2= 52.05 Kg/cm^2

Both the stresses are well within the permissible values.

Stresses in the shell at mid – span:

The stress at the span is

$$f_3 = \frac{M_2}{\pi R^2 (t - C)}$$

$$= \frac{1348}{\pi (0.321)^2 x (0.004 - .0015)}$$

$$= 166.46 Kg / cm^2$$

Axial stress in the shell due to internal pressure.

$$fp = \frac{PDi}{4t} = \frac{0.6x635}{4x4}$$

$$= 238 Kg / cm^2$$

The combined stresses (f_p +f_1), (f_p +f_3), (f_p-f_2), are well within the permissible values.