

6.PROCESS DESIGN:

(A) REACTOR(Major equipment):

Sulfonator is a continuous stirred tank reactor.

It is assumed that reaction takes place only in the reactor.

The reaction is given by

Alkyl benzene + oleum --> alkyl benzene sulfonic acid + sulfuric acid

Since oleum is used in large amount the reaction is pseudo first order.

The rate of the reaction is given by

$$(-r_A) = C_A [2667 (X_A - \frac{1}{2} X_w + \frac{1}{4} X_S)^{-9.329 + 5349/T}]$$

Where

X_A - mole fraction of H_2SO_4

X_w - mole fraction of water

X_s - mole fraction of alkyl aryl sulfonic acid

T - abs temp

C_A - concentration of alkyl aryl sulfonic acid (moles / lit)

$(-r_A)$ - rate (moles /hr/lit)

X_A - 0.598

X_S - 0.307

X_w - 0.095

T - 303 K

Density of oleum = 1830 kg/m^3

Density of alkyl benzene = 840 kg/m^3

Flowrate of oleum = 7029.4 kg/hr

Flowrate of alkyl benzene = 6386.7 kg/hr

$$\text{Total volumetric feed rate} = (6386.7 / 840) + (7029.4 / 1830)$$
$$v_0 = 11.44 \text{ m}^3/\text{hr}$$

$$\text{Initial concentration of alkyl benzene} = C_{A0} = F/v$$

$$F = \text{molar flow rate(input)}$$

$$= 25960 \text{ moles / hr}$$

$$v = \text{volumetric flow rate}$$

$$= 7.60 \text{ m}^3/\text{hr}$$

$$C_{A0} = 25960 / 7.6$$

$$= 3451.1 \text{ moles /m}^3$$

$$= 3.4 \text{ mole /lit}$$

Assuming constant density system,

$$C_A = C_{A0}(1-X_A)$$

C_A –Final concentration

Conversion, $X_A = 98\%$

$$C_A = 3.4(1-0.98)$$

$$= 0.068 \text{ moles / lit.}$$

For different concentration, rate is found &

Graph of $(-1/r_A)$ vs C_A is plotted.

Table:

C_A (moles/lit)	$(-r_A)$ (moles/hr/lit)	$(-1/r_A)(\times 10^2)$
3.4	303.3	0.33
3.07	270	0.37
2.75	243.3	0.411
2.44	212.8	0.47
2.07	181.8	0.55
1.74	153.8	0.65
1.4	123.5	0.81
0.737	66.7	1.5
0.402	35.7	2.8
0.068	5.99	16.7

From the graph of $(-1/r_A)$ vs C_A

Area under the curve = 0.7

Residence time, $\tau = 0.7$ hr

Volume of the reactor, $V = v_0 \times \tau$

$$= 11.44 \times 0.7$$

$$= 8 \text{ m}^3$$

$$(\pi d^2 / 4) \times l = V$$

Where

d-Dia of the reactor

l-Height of the reactor

By taking $(l/d) = 2$

$$V = (\pi d^2 / 4) \times 2d$$

Dia of the reactor, $d = 1.72$ m

Height of the reactor, $l = 3.44$ m

(B)HEAT EXCHANGER:

(Minor equipment)

Total amount of heat to be removed, $Q = 684.8 \text{ KJ/sec}$

Hot fluid - Mixture of reaction product & oleum

Cold fluid – water

$$Q = mC_p\Delta t$$

Mass flow rate of liquid mixture, $m = 3.72 \text{ Kg/sec}$

Specific heat of liquid mixture, $C_p = 2.092 \text{ KJ/KgK}$

Outlet temp = 30°C

$$\Delta t = 88^\circ\text{C}$$

Inlet temp = 118°C

Let inlet temperature of water = 20°C &

Outlet temperature = 40°C

Specific heat of water = 4.18 KJ/KgK

$$\begin{aligned} \text{Mass flow rate of water} &= 684.8 / (4.18 \times 20) \\ &= 8.2 \text{ kg/hr} \end{aligned}$$

Routing of fluids:

Water which has the high flow rate is taken in tube side.

Liquid mixture which has viscosity higher than water is taken in shell side.

LMTD:

Liquid mixture	Water	Δt
$\downarrow 118^\circ\text{C}$	40°C	78°C
30°C	$\uparrow 20^\circ\text{C}$	10°C

$$\text{LMTD} = (78 - 10) / \ln(78/10) = 33.10$$

For $R = 4.4$ and $S = 0.19$

$$F_T = 0.76$$

$$(\text{LMTD})_{\text{cor}} = 0.76 \times 33.10 = 25.16$$

Heat transfer area:

$$U = 750 \text{ W/m}^2\text{K}$$

$$\begin{aligned}
 \text{Area} &= Q / (\text{LMTD} \times U) \\
 &= (684.8 \times 10^3) / (750 \times 25.16) \\
 &= 36.29 \text{ m}^2 \\
 \text{Length} &= 10\text{ft} = 3.054 \text{ m}
 \end{aligned}$$

Let us take

3/4" O.D. tubes , 12 BWG gauge

$$D_o = 19.05 \text{ mm}$$

$$D_i = 13.25 \text{ mm}$$

External surface per m length = 0.05948 m

$$\begin{aligned}
 \text{Heat transfer area} &= 0.05948 (3.054 - 50 \times 10^{-3}) [50\text{mm allowance}] \\
 &= 0.179 \text{ m}^2 \text{ per tube}
 \end{aligned}$$

$$\text{Number of tubes} = 36.29 / 0.179 = 202$$

Choosing TEMA L or M type:

208 tubes (Nt) , 4 passes (Np) , one shell pass.

Shell ID= 438mm, pitch = 1 inch(triangular)

$$\begin{aligned}
 \text{Corrected area} &= 0.179 \times 208 \\
 &= 37.23 \text{ m}^2
 \end{aligned}$$

$$\begin{aligned}
 \text{Corrected } U &= (684.8 \times 10^3) / (37.23 \times 25.16) \\
 &= 731 \text{ W/m}^2\text{K}
 \end{aligned}$$

Fluid velocities:

Tube side - water

Properties: Specific heat = 4.18 kJ/kg k

$$\text{Density} = 996 \text{ kg/m}^3$$

$$\text{Viscosity} = 0.85 \text{ cP}$$

$$\text{Thermal conductivity} = 0.61 \text{ W/mK}$$

$$\begin{aligned}
 \text{Flow area, } a_t &= ((\Pi \times (D_i)^2) / 4) \times (N_t / N_p) \\
 &= (\Pi (13.25 \times 10^{-3})^2 / 4) \times (208 / 4)
 \end{aligned}$$

$$= 7.35 \times 10^{-3} \text{ m}^2$$

Velocity, $V_t = \text{mass flow rate} / (\text{density} \times \text{area})$

$$= 8.2 / (996 \times 7.35 \times 10^{-3})$$

$$= 1.23 \text{ m/sec}$$

Shell side – Liquid mixture

Properties - Density - 1238 kg/m^3

Specific heat - 2.093 KJ/kg K

Viscosity - 1.5 cP

Thermal conductivity - 0.176 W/mK

Cross flow area at center of the shell, $S_m = ((P^1 - D_o)L_s)(D_s / P^1)$

$D_o = 19.02 \text{ mm}$

$P^1 = 1 \text{ inch}$

$D_s = \text{Shell ID}$

$L_s = \text{Baffle pitch} = 0.2 D_s = 0.2 \times 0.438 = 0.0876 \text{ m}$

Number of baffles $= (L / L_s) - 1$

$$= (3.054 / (0.2 \times 0.438)) - 1$$

$$= 30$$

$$S_m = ((25.4 - 19.02) \times 0.438 \times 0.2 \times 0.438) / 25.4$$

$$= 9.6 \times 10^{-3} \text{ m}^2$$

Velocity, $V_s = 3.72 / (1238 \times 9.6 \times 10^{-3})$

$$= 0.31 \text{ m/sec}$$

Heat transfer coefficients:

Tube side:

$$Re = (V_t D_{ip}) / \mu$$

$$= (13.25 \times 10^{-3} \times 1.23 \times 996) / (0.85 \times 10^{-3})$$

$$= 20,184$$

$$\text{Pr} = C_p \mu / K$$

$$\begin{aligned} &= (0.85 \times 4.18) / 0.61 \\ &= 5.82. \end{aligned}$$

$$\text{Nu} = 0.023(\text{Re})^{0.8}(\text{Pr})^{0.4}$$

$$= 129.33$$

$$h_i = (129.33 \times 0.61) / (13.25 \times 10^{-3})$$

$$= 5954 \text{ W/m}^2\text{K}$$

Shell side:

$$\text{Re} = (V_s D_o \rho) / \mu$$

$$\begin{aligned} &= (0.31 \times 19.05 \times 10^{-3} \times 1238) / (1.5 \times 10^{-3}) \\ &= 4968.3 \end{aligned}$$

$$\text{Pr} = \mu C_p / K$$

$$\begin{aligned} &= (1.5 \times 2.093) / 0.176 \\ &= 15.07 \end{aligned}$$

$$j_H = 10^{-2}$$

$$\text{Nu} = 10^{-2} \times 4968.3 \times (15.07)^{1/3}$$

$$= 122.76$$

$$h_o = (0.176 \times 122.76) / 0.01905$$

$$= 1134.19 \text{ W/m}^2\text{K}$$

Overall heat transfer coefficient:

$$(1/U_{od}) = (1/h_o) + (D_o/D_i)(1/h_i) + (D_o \ln(D_o/D_i)) / 2K_w \text{ (clean)}$$

$$K_w = 50$$

$$1/U_{od} = 1.16 \times 10^{-3}$$

$$1/U_{od} = 1.16 \times 10^{-3} + 2 \times 10^{-4} \text{ (dirt)}$$

$$U_{od} = 735 \text{ W/m}^2\text{K}$$

Pressure drop:

Tube side:

$$Re = 20184$$

$$f = 0.079 (20.184)^{-0.25} \\ = 6.63 \times 10^{-3}$$

$$\Delta P_L = (4fLVt^2 \rho g) / (2gDi)$$

$$= (2 \times 6.63 \times 0.001 \times 3.054 \times 1.2 \times 1.2 \times 996) / 0.01325$$

$$= 4192 \text{ N/m}^2$$

$$\Delta P_E = 2.5(\rho Vt^2/2)$$

$$= 1798.8 \text{ N/m}^2$$

$$(\Delta P)_{\text{total}} = Np(\Delta P_L + \Delta P_E)$$

$$= 4(4192 + 1792.8)$$

$$= 23.93 \text{ KPa}$$

Shell side:

Cross flow zones:

$$\Delta P_c = (fk b W^2 N_c / \rho S m^2) \times (\mu_w / \mu_b)^{0.14}$$

$$b = 2 \times 10^{-3}$$

$$fk = 0.08$$

$$W = 3.72 \text{ kg/sec}$$

$$S m = 9.6 \times 10^{-3}$$

N_c -No. of tube rows crossed in each cross flow region.

P_p -Pitch parallel to flow

$$= 22$$

l_c =Baffle cut

=25% of Ds

$$N_c = \frac{D_s \left[1 - 2 \frac{l_c}{D_s} \right]}{P_p}$$
$$= 438 \left(1 - 2 \frac{0.25 \times 0.438}{0.438} \right) / 22$$
$$= 9.95 = 10$$

$$\Delta P_c = \frac{2 \times 10^{-3} \times 3.72^2 \times 0.08 \times 10}{1238 \times (9.6 \times 10^{-3})^2}$$
$$= 0.194 \text{ Kpa}$$

End Zones:

$$\Delta P_e = \Delta P_c \left[1 + \frac{N_{aw}}{N_c} \right]$$

Naw = No. of effective cross flow rows in each window =

$$= 0.8 \times l_c / P_p$$
$$= 0.8 \times 0.25 \times 438 / 22$$
$$= 3.98 = 4$$

$$\Delta P_e = 0.194 \left(1 + 4/10 \right)$$
$$= 0.27 \text{ KPa}$$

Window zones:

$$\Delta P_w = (bW^2(2 + 0.6N_{aw})) / (S_m S_{wp})$$

$$b = 5 \times 10^{-4}$$

Sw-area for flow through window

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

S_{wg} = Cross window area

S_{wt} = area occupied by the tubes

$$S_{wt} = N_t / 8 (1 - F_c) \pi D_o^2$$
$$= 208 / 8 [1 - 0.7] \times \pi (19.05 \times 10^{-3})^2$$

$$=8.89 \times 10^{-3}$$

$$S_{wg} = 38 \text{ in}^2 = 0.0245 \text{ m}^2$$

$$S_w = 0.0156 \text{ m}^2$$

$$\Delta P_w = \frac{5 \times 10^{-4} \times 3.72^2 [2 + 0.6 \times 4]}{0.0156 \times 1238 \times 9.96 \times 10^{-3}}$$
$$= 0.16 \text{ KPa}$$

$$(\Delta P)_{\text{total}} = 2 \times \Delta P_e + (N_b - 1) \Delta P_c + N_b (\Delta P_w)$$
$$= 2 \times 0.27 + (34 - 1) \times 0.194 + 34 \times 0.16$$
$$= 12.86 \text{ KPa}$$

7. MECHANICAL DESIGN

(A) Reactor

Vessel shell internal diameter – 1.72m

Internal pressure – 2.04 Kg/cm²

Design pressure – 2.44 Kg/cm²

Material – openhearth steel (IS-2002)

Allowable stress – 980 Kg/cm²

Shell thickness :

$$t_s = PDi/(2fJ - P)$$

J = Joint efficiency factor

$$= 0.85$$

$$t_s = (2.44 \times 1720)/(2 \times 0.85 \times 980 - 2.44)$$

$$= 2.52 \text{ mm}$$

Use 4 mm thickness including corrosion allowance

Agitator:

Diameter of agitator – 525 mm (Da)

Speed (maximum) – 200 rpm

Overhang of agitator shaft between bearing and agitator – 1300 mm (l)

Agitator blades – 6 (n)

Width of the blade – 75 mm (w)

Thickness of blade – 8 mm (t)

Shaft material – commercial cold rolled steel

Permissible shear stress in shaft – 550 Kg/cm²

Elastic limit in tension – 2460 Kg/cm²

Modulus of elasticity – 19.5 x 10⁵ Kg/cm² (E)

Permissible stress for key (carbon steel)

Shear – 630 Kg/cm²

Crushing – 1300 Kg/cm²

Stuffing box (carbon steel) - 950 Kg/cm²

Studs and bolts (hot rolled carbon steel)

Permissible stress – 587 Kg/cm²

It is assumed that vessel geometry conforms to the standard tank configuration

$$\rho N d a^2 / \mu = 1.4 \times 10^3 \times 200/60 \times (500/1000)^2 / 1.7 \times 10^{-2}$$

$$= 683.52 \times 10^2 > 10,000$$

From power curve, $N_p = 6$

$$\begin{aligned} \text{Power, } P &= N_p \rho N^3 D a^5 / (g_c \times 75) \\ &= (6 \times 1.4 \times 10^3 \times (200/60)^3 \times (500/1000)^5) / (9.81 \times 75) \\ &= 13.22 \text{ hp} \end{aligned}$$

Gland losses (10%) – 1.322 hp

Power input = 13.22 + 1.3 = 14.52 hp

$$\begin{aligned} \text{Transmission system losses (20\%)} &= 14.52 \times 0.2 \\ &= 2.904 \text{ hp} \end{aligned}$$

Total hp = 14.52 + 2.904 = 17.42

This will be taken as 18.5 hp to allow for fitting losses

Shaft design

Continuous average rated torque on the agitator shaft,

$$\begin{aligned} T_c &= (\text{hp} \times 75 \times 60) / (2 \pi N) \\ &= (18.5 \times 75 \times 60) / (2 \pi \times 200) \\ &= 66.25 \text{ Kg m} \end{aligned}$$

Polar modulus of the shaft,

$$Z_p = T_m / f_s$$

$$T_m = 1.5 T_c$$

f_s – shear stress – 550 kg/cm²

$$\begin{aligned} Z_p &= (1.5 \times 66.25 \times 100) / 550 \\ &= 18.07 \text{ cm}^3 \end{aligned}$$

$$\pi d^3 / 16 = 18.07$$

$$d = 4.5 \text{ cm}$$

Diameter of shaft = 5 cm

$$\text{Force, } F_m = T_m / 0.75 R_b$$

R_b – Radius of blade

$$F_m = (1.5 \times 66.25 \times 100) / (0.75 \times 25) \\ = 530 \text{ Kg}$$

Maximum bending momentum

$$M = F_m \times l \\ = 530 \times 1.3 \\ = 689 \text{ Kg-m}$$

Equivalent bending moment

$$M_e = \frac{1}{2} \left[M + \sqrt{M^2 + T_m^2} \right] \\ = \frac{1}{2} \left[689 + \sqrt{689^2 + 99.4^2} \right] \\ = 692.5 \text{ Kg .m}$$

The stress due to equivalent bending

$$F = M_e / Z \\ Z = \pi(5)^3 / 32 \text{ (Modulus of reaction of the shaft cross section)} \\ = 12.27 \\ f = (692.5 \times 100) / 12.27 \\ = 5642.9 \text{ kg/cm}^2$$

Stress f is higher than the permissible elastic limit (2460 Kg/Cm^2). Therefore use a 7 cm diameter shaft for which the stress will be

$$f = 2056 \text{ Kg/cm}^2$$

$$\text{Deflection of shaft, } \delta = (Wl^3) / (3 EI) \quad [W = F_m] \\ = (130)^3 \times 530 / 3 \times 19.5 \times 10^5 \times \pi \times 7^4 / 64 \\ = 1.69 \text{ cm}$$

$$\text{Critical speed, } N_c = (4.987 \times 60) / \sqrt{\delta}$$

$$= 230.16 \text{ rpm}$$

Since actual shaft speed is 200 rpm which is 87% of the critical speed it is necessary to increase the value of critical speed by decreasing the deflection.

Choose therefore a 8cm dia shaft.

Then,

$$\delta = 1.00 \text{ cm}$$

$$N_c = 60 \times 4.987 / 1.00 = 300 \text{ rpm}$$

Actual speed is 66.6 % of the critical speed

Blade design:

$$\begin{aligned} F &= (\text{maximum torque}) / (t w^2 / n) \\ &= 99.375 / (0.8 \times 7.5^2 / 6) \\ &= 132.5 \text{ Kg/cm}^2 \end{aligned}$$

Stress is well within the limit

Hub and key design:

$$\begin{aligned} \text{Hub diameter of agitator} &= 2 \times \text{shaft diameter} \\ &= 16 \text{ cm} \end{aligned}$$

$$\text{Length of the hub} = 2.5 \times 8 = 20 \text{ cm}$$

$$\text{Length of key} = 1.5 \times \text{shaft dia} = 12 \text{ cm}$$

$$T_{\max} / (d/2) = l b f_s = (l t / 2) f_c = 99.25 \times 100 / (8/2)$$

f_s - shear stress in key

f_c – stress in crushing of key

$$12 \times b \times 650 = 12 \times t / 2 \times 1300 = 2481.25$$

$$b = 3.18 \text{ mm}$$

$$t = 3.18 \text{ mm}$$

Use 4mm x 4mm x 12 cm key

Stuffing box and gland:

$$b = d + \sqrt{d}$$

$$= 8 + \sqrt{8} = 10.28 \text{ cm}$$

Permissible stress in the material of stuffing box,

$$t = Pb/2f + C$$

$$t = (2.44 \times 10.28 \times 10 / 2 \times 950) + 6$$

$$= 6.13 \text{ mm}$$

$$a = b + 2t$$

$$= 10.28 + 2 \times 0.613$$

$$= 11.51 \text{ cm}$$

Load on gland,

$$F = (\pi/4) p(b^2 - d^2)$$

$$= (\pi/4)(10.28^2 - 8^2)2.44$$

$$= 79.87 \text{ Kg}$$

Size of the stud:

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

$$n - \text{no of stud} = 4$$

f – permissible stress for stud

$$= 587 \text{ Kg/cm}^2$$

$$d_0^2 = 0.043 \text{ cm}$$

$$d_0 = 0.658 \text{ mm}$$

Minimum stud diameter – 15 mm

$$\text{Flange thickness} = 1.75 \times 15$$

$$= 27.25 = 30 \text{ mm}$$

Coupling: -

A clamp coupling of cast iron is used

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

Wind pressure, $P_w = kph.Do.$

k-Coefficient depending on the shape factor

$$= 0.7$$

$$P_w = 0.7 \times 128.5 \times 3.44 \times 1.72$$

$$= 532.2 \text{ Kg.}$$

Maximum total compressive load in the support is

$$P = \frac{4P_w(H - F)}{NDb} + \frac{\Sigma W}{n}$$

H – Height of the vessel above the foundation

F – Vessel clearance from foundation to vessel bottom.

ΣW – Maximum weight of the vessel

n = number of brackets

$$P = \frac{4 \times 532.2(4.440 - 1)}{4 \times 1.9} + \frac{10000}{4}$$

$$= 3463.5 \text{ Kg.}$$

Bracket:

(a) Base plate:

Suitable base plate size, a = 140 mm

$$B = 150 \text{ mm}$$

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

$$P_{av} = (3463)/(14 \times 15) = 16.5 \text{ Kg/cm}^2$$

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

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

$$= 0.7 \times 16.5 \times \frac{15^2}{T^2} \left(\frac{14^2}{15^2 + 14^2} \right)$$

$$= \frac{1209}{T^2}$$

$$f = 1575 \text{ Kg} / \text{cm}^2$$

(given)

$$\therefore T_1 = 8.7 \text{ mm}$$

Use a 9 mm thick plate.

(b) Web plate.

Bending moment of each plate =

$$\frac{P (D_{im} - D)}{2} \times 100$$

$$= \frac{(3463)(1.9 - 1.72)}{4}$$

$$= 15583.5 \text{ Kg} \cdot \text{cm}$$

$$\text{Stress at the edge, } f = \frac{15583.5}{T_2 \times 14 \times 14} \times \frac{1}{0.707}$$

$$= 112.5 / T_2$$

$$\text{For } f = 1575, \quad T_2 = 7 \text{ mm}$$

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 cm²

Modulus of section – 19.4 cm³

Radius of gyration, r – 2.21 cm

Weight – 16.4 Kg/m

Height from foundation, l = 1.8m

Equivalent length for fixed ends $l_e = l/2$
= 0.9 m

$$\text{Slenderness ratio} = l_e/r = \frac{0.9 \times 100}{2.21} = 40$$

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

$$f = \frac{\sum W}{Axn} + \frac{\sum WxL}{nxZ}$$

$\sum w$ = Load on column

A – area of cross section

E – eccentricity

Z – modulus of section of cross – section

N – number of columns

$$f = \frac{3463}{20.88 \times 1} + \frac{3463 \times 4.5}{1 \times 19.4}$$

$$= 969 \text{ Kg / cm}^2$$

Channel selected is satisfactory.

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 – $0.8 \times 75 + 2 \times 20 = 100\text{mm}$

Side C – $0.95 \times 150 + 2 \times 20 = 182.5 \text{ mm}$

$$\begin{aligned} \text{Bearing pressure, } P_b &= (3463/4) \times (1/10 \times 18.25) \\ &= 4.74 \text{ Kg/cm}^2 \end{aligned}$$

This is less than the permissible bearing pressure for concrete.

$$\text{Stress in the plate, } f = \left[\frac{\frac{7.14}{2} \times \frac{20^2}{10}}{\frac{t^2}{6}} \right] = 85.6/t^2$$

For $f = 1575 \text{ Kg/cm}^2$

$$t = 2.33 \text{ mm}$$

It is usual to select a plate 4 to 6 mm thick.

(B)Shell & Tube heat exchanger:

Shell side:

Material – carbon steel

Working pressure – 0.1N/mm^2

Design pressure – 0.11N/mm^2

Permissible stress for carbon steel – 95 N/mm^2

Dia of shell= 438mm

Tube side:

Working pressure= 0.5N/mm^2

Design pressure= 0.55N/mm^2

Shell thickness:

$$t_s = \frac{PD}{2fJ+P} = \frac{0.11 \times 438}{2 \times 95 \times 0.85 + 0.11}$$

$$= 0.3 \text{ mm}$$

Minimum thickness of shell must be 6.3 mm

Including corrosion allowance, $t_s = 8 \text{ mm}$.

Head thickness: Shallow dished & torispherical head

$$t_h = \frac{PRcW}{2fJ}$$

Rc – crown radius

W – stress intensification factor

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

$$Rk = 6\% Rc$$

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

$$J = 1$$

$$t_h = \frac{0.11 \times 1.77 \times 438}{2 \times 95}$$

$$= 0.45 \text{ mm}$$

Use thickness as same for shell i.e. 8 mm

Transverse baffles:

Baffle spacing = $0.2 \times 438 = 87.6$ mm

Thickness of baffles = 6 mm

Tie rods and spaces:

Diameter of tie rod = 10 mm

Number of tie rods = 6

Flanges:

Shell thickness = $g_o = 8$ mm

Flange material – IS: 2004 – 1962 class 2

Gasket material – asbestos composition

Bolting steel = 5% Cr Mo steel

Allowable stress of flange material – $100 \text{ MN} / \text{m}^2$

Allowable stress of bolting material, S_g – $138 \text{ MN}/\text{m}^2$

Outside dia = $B = 438 + (2 \times 8)$

$$= 454 \text{ mm}$$

Gasket width:

$$\frac{d_o}{d_i} = \left[\frac{y - pm}{y - p(m + 1)} \right]^{\frac{1}{2}}$$

m – gasket factor – 2.75

y – min design seating stress – $25.5 \text{ MN}/\text{m}^2$

Gasket thickness = 1.6 mm

$$\frac{d_o}{d_i} = \left[\frac{25.5 - 0.11 \times 2.75}{25.5 - 0.11(2.75 + 1)} \right]^{\frac{1}{2}}$$

$$= 1.002$$

Let d_i of the gasket equal 464 mm [10 mm greater than shell dia]

$$d_o = 0.464 \times 1.002$$

$$= 0.4649\text{m}$$

$$\begin{aligned}\text{Mean gasket width} &= (0.4649 - 0.464)/2 \\ &= 5 \times 10^{-4}\end{aligned}$$

Taking gasket width of 12 mm,

$$d_o = 0.488 \text{ m}$$

Basic gasket seating width, $b_o = 5\text{mm}$

Diameter of location of gasket load reaction is,

$$\begin{aligned}G &= d_i + N \\ &= 0.464 + 0.012 \\ &= 0.476\text{m}\end{aligned}$$

Estimation of bolt loads:

Load due to design pressure:

$$\begin{aligned}H &= \frac{\pi G^2 P}{4} = \frac{\pi (0.476)^2 \times 0.11}{4} \\ &= 0.0196 \text{ MN}\end{aligned}$$

Load to keep joint tight under operation

$$\begin{aligned}H_p &= \pi G (2b) m_p \\ &= \pi \times 0.476 \times 2 \times 5 \times 10^{-3} \times 2.75 \times 0.11 \\ &= 4.52 \times 10^{-3} \text{ MN}\end{aligned}$$

Total operating load, $W_o = H + H_p$

$$= 0.024 \text{ MN}$$

Load to seat gasket under bolting up condition

$$\begin{aligned}W_g &= \pi G b_y \\ &= \pi \times 0.476 \times 0.005 \times 25.5 \\ &= 0.1906 \text{ MN}\end{aligned}$$

∴ Controlling load = 0.1906 MN

$$\begin{aligned}\text{Minimum bolting area} &= A_m = W_g / S_g \\ &= 0.1906 / 138 \\ &= 1.38 \times 10^{-3} \text{ m}^2\end{aligned}$$

Take Bolt size – M 18 x 2

Actual number of bolts – 44

$$R = 0.027 \text{ m}$$

$$g_1 = g_o / 0.707 = 1.415 g_o \text{ for weld leg}$$

$$g_o = 8 \text{ mm}$$

$$\begin{aligned}\text{Bolt circle diameter, } C &= B + 2(g_1 + R) \\ &= 0.454 + 2(1.415 \times 0.008 + 0.027) \\ &= 0.5306 \text{ m}\end{aligned}$$

Using 66 mm bolt spacing,

$$\begin{aligned}C &= 44 \times 0.066 / \pi \\ &= 0.9243 \text{ m}\end{aligned}$$

∴ Bolt circle diameter, C = 0.93 m

Flange outside diameter

$$\begin{aligned}A &= C + \text{bolt diameter} + 0.02 \text{ m (minimum)} \\ &= 0.93 + 0.018 + 0.02 \\ &= 0.968 = 0.97 \text{ m}\end{aligned}$$

Check of gasket width

$$\frac{AbSg}{\pi GN} = \frac{1.56 \times 10^{-4} \times 44 \times 138}{\pi \times 0.012 \times 0.4 \times 0.475}$$

$$= 50.43 < 2y$$

It is satisfied

Flange moment computation:

For operating condition:

$$W_0 = W_1 + W_2 + W_3$$

$$W_1 = \pi(B^2/4)P$$

$$= \pi/4(0.454)^2 0.11$$

$$= 0.0178$$

$$W_2 = H - W_1$$

$$= 0.0196 - 0.0178$$

$$= 1.79 \times 10^{-3}$$

$$W_3 = W_0 - H = H_p \text{ (gasket load)}$$

$$= 4.52 \times 10^{-3} \text{ MN}$$

Total flange moment, $M_0 = W_1 a_1 + W_2 a_2 + W_3 a_3$

$$a_1 = \frac{C - B}{2} = \frac{0.93 - 0.454}{2} = 0.238$$

$$a_3 = \frac{C - B}{2} = \frac{0.93 - 0.454}{2} = 0.23$$

$$a_2 = \frac{a_1 + a_3}{2} = 0.23$$

$$M_0 = 5.68 \times 10^{-3}$$

For bolting up condition

$$Mg = W \cdot a_3$$

$$W = (A_m + A_b)/(2) \cdot S_g$$

A_b = area of bolt

$$= 44 \times 1.56 \times 10^{-4}$$

$$= 6.76 \times 10^{-3} \text{ m}^2$$

A_m = Minimum bolt area

$$=1.38 \times 10^{-3} \text{m}^2$$

$$S_g = 138 \text{N/mm}^2$$

$$W = 0.562 \text{ MN}$$

$$a_3 = 0.23$$

$$M_g = 0.1275 \text{ MN-m}$$

M_g is controlling moment

Flange thickness:

$$t^2 = (MC_f Y) / (B S_t) = (MC_f Y / B S_f o)$$

$$K = (A/B)$$

$$= (0.97 / 0.454)$$

$$= 2.13$$

Assume $C_f = 1$

From the graph, $Y = 3$

$$M = 0.1275 \text{ MN-m}$$

$S_t =$ Allowable stress

$$= 100 \text{ MN/m}^2$$

$$t^2 = (0.1275 \times 3) / (0.454 \times 100)$$

$$= 0.0008$$

$$t = 0.029 \text{ m}$$

Tube sheet thickness:

$$t_{ts} = FG \sqrt{\frac{0.025 \times P}{6}}$$

$$= 1 \times 0.475 \sqrt{\frac{0.25 \times 0.55}{95}}$$

$$= 18.07 \text{ mm}$$

$t_{ts} = 21$ mm including corrosion allowance

Channel and channel cover:

$$th = Gc \sqrt{\frac{KP}{6}}$$

$$0.475 \sqrt{\frac{0.3 \times 0.55}{95}}$$

$$= 19 \text{ mm}$$

$t_h = 22$ mm including corrosion allowance.

Nozzle:

Thickness of nozzle = $PD/2fJ-P$

Inlet & outlet dia – 100 mm

Vent – 50 mm

Drain – 50 mm

Opening for relief valve – 75 mm

$$tn = \frac{0.55 \times 100}{2 \times 95 \times 1 - 0.55}$$

$$= 0.293$$

Corrosion allowance 3 mm

$$tn = 4 \text{ mm}$$

Considering the size of the nozzle & the pressure rating, it is necessary to provide for a reinforcing pad on the channel cover.

Area required to be compensated for each nozzle

$$A = d \times t_h = 100 \times 22 = 2200 \text{ mm}^2$$

Saddle Support:

Material- low carbon steel

Diameter = 454 mm

Length of the shell, L = 3.054 m

Knuckle radius = 6% of diameter

$$= 27.24 \text{ mm}$$

Total depth of head =

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

$$= \sqrt{\frac{454 \times 27.24}{2}}$$

$$H = 78.63 \text{ mm}$$

Weight of vessel & contents, W = 11943 kg.

Distance of saddle center line from shell end,

$$A = 0.5 \times R = 113.5 \text{ mm}$$

Longitudinal bending moments:

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

Q = Load carried by each symmetrical support

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

$$= \frac{11943}{2} \left[3.05 + \frac{4}{3} \times 0.078 \right]$$

$$= 18834.1 \text{Kg}$$

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

$$M_1 = 12.778 \text{Kg.m}$$

$$M_2 = 10218 \text{Kg.m}$$

Stresses in shell at the saddle

1. At the topmost fibre of the cross section.

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

t = thickness of the shell

$$f_1 = \frac{12.778}{\pi \times 0.008 \times 0.227^2}$$

$$= 0.9865 \text{Kg/cm}^2$$

2. At the bottom most fibre of the cross – section

$$f_2 = \frac{M_1}{k_1 \pi R^2 t}$$

$$K_2=1$$

$$F_2= 0.9865 \text{ Kg/cm}^2$$

Stresses are well within the permissible values.

Stresses in the shell at mid – span:

The stress at the span is ,

$$f_3 = \frac{M_2}{\pi R^2 t}$$

$$= \frac{10225.35}{\pi(0.227)^2 \times 0.008}$$

$$= 789.46 \text{ Kg/cm}^2$$

Axial stress in the shell due to internal pressure :

$$f_p = \frac{PDi}{4t} = \frac{1.12 \times 438}{4 \times 8}$$

$$= 15.34 \text{ Kg/cm}^2$$

$$f_3 + f_p = 804.80 \text{ kg/cm}^2$$

Stresses are well within the permissible values.