International Journal of Innovative Research in Advanced Engineering (IJIRAE) ISSN: 2349-2163
Issue 1, Volume 2 (January 2015) www.ijirae.com

Design of Atmospheric Distillation Unit for Tray Column

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Abstract - Separation operations achieve their objective by the creation of two or more coexisting zones which differ in temperature, pressure, composition, and/or phase state.

Keywords – Distillation, Atmospheric, Process description, Designing and Shell thickness.

I. Introduction to Distillation & Atmospheric Distillation

A. Introduction to Distillation Operations

Each molecular species in the mixture to be separated responds in a unique way to differing environments offered by these zones. Consequently, as the system moves toward equilibrium, each species establishes a different concentration in each zone, and these results in a separation between the species. The separation operation called distillation utilizes vapour and liquid phases at essentially the same temperature and pressure for the co-existing zones. Various kinds of devices such as random or structured packing's and plates or trays are used to bring the two phases into intimate contact.

Trays are stacked one above the other and enclosed in a cylindrical shell to form a column. Packing's are also generally contained in a cylindrical shell between hold-down and support plates. The column may be operated continuously or in batch mode depending on a number of factors such as scale and flexibility of operations and solids content of feed. The feed material, which is to be separated into fractions, is introduced at one or more points along the column shell. Because of the difference in density between vapor and liquid phases, liquid runs down the column, cascading from tray to tray, while vapour flows up the column, contacting liquid at each tray. Liquid reaching the bottom of the column is partially vaporized in a heated re-boiler to provide boil-up, which is sent back up the column. The remainder of the bottom liquid is withdrawn as bottoms, or bottom product. Vapour reaching the top of the column is cooled and condensed to liquid in the overhead condenser. Part of this liquid is returned to the column as reflux to provide liquid overflow. The remainder of the overhead stream is withdrawn as distillate, or overhead product. In some cases only part of the vapor is condensed so that a vapour distillate can be withdrawn.

This overall flow pattern in a distillation column provides counter-current contacting of vapor and liquid streams on all the trays through the column. Vapour and liquid phases on a given tray approach thermal, pressure, and composition equilibria to an extent dependent upon the efficiency of the contacting tray. The lighter (lower-boiling temperature) components tend to concentrate in the vapor phase, while the heavier (higher-boiling temperature) components concentrate in the liquid phase.

The result is a vapor phase that becomes richer in light components as it passes up the column and a liquid phase that becomes richer in heavy components as it cascades downward. The overall separation achieved between the distillate and the bottoms depends primarily on the relative volatilities of the components, the number of contacting trays in each column section, and the ratio of the liquid-phase flow rate to the vapour-phase flow rate in each section.

If the feed is introduced at one point along the column shell, the column is divided into an upper section, which is often called the rectifying section, and a lower section, which is often referred to as the stripping section. In multiple-feed columns and in columns from which a liquid or vapor side stream is withdrawn, there are more than two column sections between the two end-product streams.

The notion of a column section is a useful concept for finding alternative systems (or sequences) of columns for separating multicomponent mixtures, as described below in the subsection Distillation Systems. All separation operations require energy input in the form of heat or work. In the conventional distillation operation, as typified in figure given below, energy required to separate the species is added in the form of heat to the re-boiler at the bottom of the column, where the temperature is highest. Also heat is removed from a condenser at the top of the column. Here as shown in fig. 1 plate type distillation tower with re-boiler and condenser.

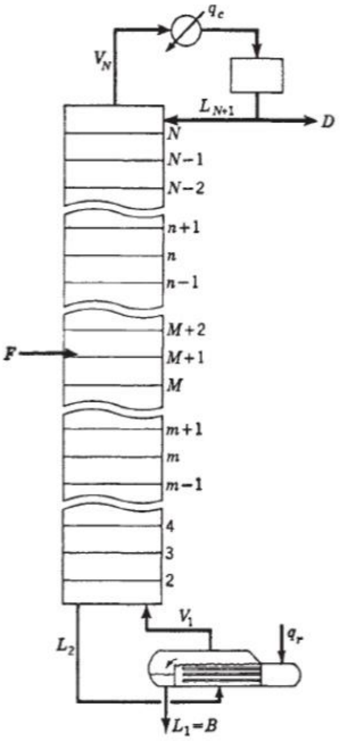

Fig. 1 Typical diagram of plate type distillation tower with re-boiler and condenser

B. *Introduction to Atmospheric Distillation*

A physicochemical process used to separate component products of a mixture, using differences in the boiling point temperatures of individual components. In the process of atmospheric distillation, individual fractions of gases, benzene, paraffin and diesel oils become separated.

Atmospheric distillation is the first major process in a refinery. All crude oil entering the refinery, after desalting, passes through the atmospheric distillation column on its way to further processing in downstream process units. If there is a shutdown of the atmospheric distillation column it means that the entire refinery is essentially shut down. Crude oil enters the atmospheric distillation column at 2, 4-5, 2 bar / 35-75 psig and approximately 370 °C / 700 °F. At this pressure and temperature the fluid is in a liquid/vapor state. In this condition the crude immediately begins to separate upon entering the atmospheric distillation column. Light vapours rise to the top of the column and heavier liquid hydrocarbon fall to the bottom and the separation process begins. Hydrocarbon fractions are drawn from the tower and sent to additional downstream units to be processed into feed stock or blending components.

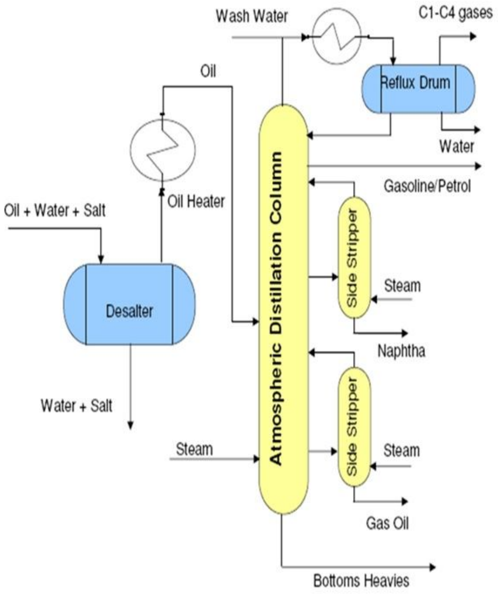

Fig. 2 Typical PFD for an Atmospheric Distillation Unit

C. *Process Description of Atmospheric Distillation in Oil industry*

Crude oil is sent to the atmospheric distillation unit after desalting and heating. The purpose of atmospheric distillation is primary separation of various „cuts" of hydrocarbons namely, fuel gases, LPG, naphtha, kerosene, diesel and fuel oil. The heavy hydrocarbon residue left at the bottom of the atmospheric distillation column is sent to vacuum distillation column for further separation of hydrocarbons under reduced pressure.

As the name suggests, the pressure profile in atmospheric distillation unit is close to the atmospheric pressure with highest pressure at the bottom stage which gradually drops down till the top stage of the column. The temperature is highest at the bottom of the column which is constantly fed with heat from bottoms re-boiler. The re-boiler vaporizes part of the bottom outlet from the column and this vapor is recycled back to the distillation column and travels to the top stage absorbing lighter hydrocarbons from the counter current crude oil flow. The temperature at the top of the column is the lowest as the heat at this stage of the column is absorbed by a condenser which condenses a fraction of the vapours from column overhead. The condensed hydrocarbon liquid is recycled back to the column. This condensed liquid flows down through the series of column trays, flowing counter current to the hot vapours coming from bottom and condensing some of those vapours along the way.

Thus a re-boiler at the bottom and a condenser at the top along with a number of trays in between help to create temperature and pressure gradients along the stages of the column. The gradual variation of temperature and pressure from one stage to another and considerable residence time for vapours and liquid at a tray help to create near equilibrium conditions at each tray. So ideally we can have a number of different vapor-liquid equilibria at different stages of this column with varying temperature and pressure conditions. This means that the hydrocarbon composition also varies for different trays with the variation in temperature and pressure.

The heaviest hydrocarbons are taken out as liquid flow from the partial re-boiler at bottom and the lightest hydrocarbons are taken out from the partial condenser at the column overhead. For the in between trays or stages, the hydrocarbons become lighter as one moves up along the height of the column. Various other cuts of hydrocarbons are taken out as side draws from different stages of the column. Starting from LPG at the top stages, naphtha, kerosene, diesel and gas oil cuts are taken out as we move down the stages of atmospheric column.

The heaviest hydrocarbon residue taken out from partial re-boiler is sent to the vacuum distillation column for further separation under reduced pressure. The different cuts of hydrocarbons taken out at this stage are the result of primary separation and undergo further processing before being transformed to end products.

D. *Basic Considerations for Designing of Atmospheric Distillation Column*

i. For distillation column design we usually have the following initial information
    a. Feed flow rate.
    b. Composition of feed.
    c. Temperature and pressure of feed.
    d. Heat losses from the column, usually assumed to be negligible for an initial design.
    e. Type of condenser, either total or partial. Total is the usual case.
    f. Desired key recoveries, i.e. a desired composition of a single component in either the bottoms.

ii. The procedure for designing the column is as follows
    a. Specify the operating pressure. See guidelines below.
    b. Determine the degrees of freedom of the column and the independent variables required for the design.
    c. Determine the number of trays and reflux ratio. Use McCabe - Thiele, FUEM, and simulator.
    d. Determine the feed location. Usually add at tray with identical composition.
    e. Determine heat duties for re-boiler and condenser, using an energy balance on the column.
    f. Determine column width. Use 3 ft. /sec at average temperature and pressure of column for estimation purposes, or a more detailed method.

The guidelines below are recommended for an initial design estimate only. Later heat integration calculations might change the design entirely.

1. *Pressure Considerations as the Pressure of a Column is raised:*

a. Separation becomes more difficult since the relative volatility decreases - more plates and
b. Reflux is required to achieve the separation.
c. The latent heat of vaporization decreases, reducing the duties of the re-boiler and Condenser.

d. The vapor density increases, resulting in a smaller column diameter.
e. The re-boiler temperature increases. This is usually limited by the decomposition temperature of the material being vaporized.
f. Condenser temperature increases.

As the pressure is lowered, these effects are reversed. A lower pressure limit is usually encountered by a desire to avoid vacuum operation and / or refrigeration in the condenser. For an initial design, it is adequate to set the distillation pressure to as low a pressure above ambient as allowed by cooling water or air cooling in the condenser. An initial starting value might be selected so that the bubble point of the overhead product is 10oC above the summer cooling water temperature or to atmospheric pressure if vacuum operation is suggested.

2. *Reflux Ratio Considerations:*

We have several trade-offs in the selection of a reflux ratio. As the reflux ratio is increased.

a) 1. The purity of the product is increased.
b) 2. The capital costs decrease since the number of trays is decreased.
c) 3. The energy costs increase as more re-boiling and condensing are required.

- If the optimal reflux ratio is less than 1.1 times the minimum reflux, select 1.1 times the minimum reflux since a small error in design data or operating conditions might lead to a column that does not work.

3. *Feed Considerations:*

- The feed consideration is more of an afterthought rather than a critical design parameter.
- The question is whether the feed is at the bubble point, subcooled, partial vapor, or all vapor.

In general, a sub cooled feed:

a) Decreases the number of tray in the rectifying section but increases the trays in the stripping section.
b) Increases the size of the re-boiler but decreases the size of the condenser. Partially vaporized feed reverses this.

E. *Determination of Shell Thickness for Atmospheric Distillation Column*

At the top of the column only circumferential stress & longitudinal or axial stress due to the internal pressure or vacuum are significant. If distillation column is operated under internal pressure then thickness of shell at the top of column is finding out by equation.

$$t_s = \frac{Pr_i}{fJ-0.6P} + CA \text{As per ASME code, sec VIII, div-1}$$

$$\text{OR } t_s = \frac{PD_i}{2fJ-P} + CA \text{ as per BS 5500}$$

Assume the thickness of shell t, find out L/Do, Do/t⇒ Factor A, then from factor A gives Factor B. Design External pressure (Pd) (1atm. Pressure Max.) should be less than or equal to maximum allowable external pressure.

This thickness may be satisfactory up to a certain distance from the top of the shell. Let this thickness can be used up to a distance ‘X’ form the top of the shell. In addition to circumferential stress, other stresses induced in the shell in axial direction are

1) *Axial or longitudinal stress induced due to internal pressure:*

$$f_{ap} = \frac{PDi}{4(t_s - C)}$$

This stress remains constant throughout the height.

2) *Compressive Stress Created by dead loads in axial direction:*

Compressive Stress created by weight of shell at the distance ‘X’ from the top of the shell

$$f_{ds} = \frac{Weightofshelluptoadistance X}{Crosssectionofshell}$$

$$f_{Ds} = \frac{\frac{\pi}{4}(Do^2 - Di^2)\rho_s X \frac{g}{g_c}}{\pi D_m (t_s - C)} \cong \rho_s \frac{g}{g_c} X$$

Where, D_m= Mean diameter of shell

$D_o, D_i \Rightarrow$ Outside & inside diameter of shell

$\rho_s \Rightarrow$ Density of shell plate material

Compressive stress due to weight of insulation at a distance 'X' from the top of the shell

$$f_{dins} = \frac{\pi D_{ins} t_{ins} \rho_{ins} X \frac{g}{g_c}}{\pi D_m\ (t_s - C)}$$

For D_{ins}=Average diameter of insulation
For a large column D_{ins}=D_m

Similarly compressive stress created by liquid in the column. Liquid is supported by trays & trays are supported by shell plate

$$F_{d(liq.+tray)} = \frac{(liquid + tray) Weightperuintheight X \frac{g}{g_c}}{\pi D_m\ (t_s - C)} = \frac{F_{liq+tray)}}{\pi D_m (t_s - C)}$$

$$F_{(liq+tray)X} = (\frac{X-h_1}{S} + 1) \times \frac{\pi}{4} Di^2 \times (wt.ofonetrayperunitare + wt.liquidoveronetrayperunitarea)$$

Where, h_1 = Top disengagement space
S = Tray Spacing

Stress induced by attachments such as, over overhead condensers, top head, platforms & ladders

$$f_{d(att)} = \frac{\sum wieghtofattachmentperunitheight X}{\pi D_m\ (t_s - C)}$$

∴Compressive stress due to dead load is $f_{dx} = f_{ds} + f_{d(ins)} + f_{d(liq)} + f_{d(att)}$

Stress created by wind load in shell plate or pipe at a distance X from the top

$$F_{wx} = \frac{M_x}{Z}$$

Where, Z = Modulus of Section for the area of shell = $\frac{\pi}{4} Do^2 (t_s - C)$

$$(Z = \frac{\pi}{32} \frac{Do^4 - Di^4}{D_o} = \frac{\pi}{32} (D_o - D_i)(D_o + D_i) \frac{(Do^2 + Di^2)}{D_o}$$

$$\veeeq \frac{\pi}{32} (D_o - D_i) 4\, Do^2$$

$$\cong \frac{\pi}{4} t_s Do^2$$

The column can be considered as a uniformly loaded cantilever beam fixed at one end. The stress induced in shell due to wind load is compressive on download side &tensile on upward side.

M_w = Bending moment due to wind load a distance X

∴ M_w = Wind load × distance

∴ M_w = Wind pressure ×projected area × distance

Wind pressure is acting in a direction of wind velocity. Maximum wind pressure is acting on flat surface. Wind pressure acting on cylindrical surface is less than wind pressure acting on flat surface. We can take wind pressure acting on cylindrical surface = $0.7P_w$, where P_w = wind pressure

$\therefore M_w = \frac{0.7\, P_w \times D_o X^2}{2}$

$$\therefore f_{wx} = \frac{1.4\, P_w D_o X^2}{\pi Do^2\,(t_s - C)} = \frac{1.4 P_w X^2}{\pi D_o\,(t_s - C)}$$

Stress due to eccentricity of loads: Most of the parts of tower are symmetric about the longitudinal axis of tower. But some parts like attached equipment's overhead condenser, intermediate cooler, manholes & other nozzles are not symmetric about the longitudinal axis of tower. These eccentric loads create the stress in the shell plate of tower, which is given by one general equation.

$$f_{ex} = \frac{\sum W_e\,(e)}{\frac{\pi}{4} Do^2\,(t_s - C)} = \frac{\sum M_e}{Z}$$

W_e = eccentric load, e = eccentricity, M_{ex}= bending moment created by eccentric load at distance X from top.

Stress due to seismic load: Seismic load is a vibrational load resulting from the earth quakes. Stress created by seismic load is given by equation.

$$f_{SX} = \frac{M_{SX}}{\frac{\pi}{4} Do^2\,(t_s - C)}$$

Where bending moment at a distance X created by seismic load is given by equation

$$M_{SX} = \frac{CWX^2}{3}\frac{(3H - X)}{H^2}$$

Where, C= Seismic Co-efficient.
W= Total wt. of column
H= total height of column.

The value of seismic coefficient C is in range from 0.02 to 0.2 depending on earthquake history of area. For mild seismic zone C = 0.02 to 0.05, for medium seismic zone C = 0.05 to 0.1 and for severe seismic zone, C = 0.1 to 0.2.

If there is no possibility of earthquake and stress created by eccentric load is negligible then maximum stress created in axial direction

$$f_{wx} + f_{ap} - f_{dx} = f_{tmax}$$

Where, f_{tmax}= Maximum tensile stress created in axial direction ≤ J f_{tallow}
f_{tallow} = Maximum allowable tensile stress of shell plate material.

If we substitute f_{tallow} in place f_{tmax}then we get the maximum value of X, up to which we can keep the thickness of shell plate equal to t_s,

$$f_{WX} + f_{ap} - f_{dx} = J \times f_{tallow},$$ where J= Joint efficiency

$$\frac{1.4\, P_w X^2}{\pi D_o (t_s - C)} + \frac{PD_i}{4(t_s - C)} - \frac{\sum DeadWeightperunitheight \times X}{\pi D_m (t_s - C)} - Jf_{allow} = 0$$

This equation is in the form of $aX^2 + bX + c = 0$

$$\therefore \text{X} = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

From which we can find the value of X, which is the maximum distance from the top of the shell up to which we can use the thickness of shell equal to t_s .

In this derivation we have considered only upward side. But wind load creates tensile stress in upward side and compressive stress in download stress in download side. Therefore maximum compressive stress created in axial direction.

$$f_{cmax} = f_{wx} + f_{dx} - f_{ap}$$

Maximum compressive stress should be less than or equal to maximum allowable compressive stress.
Maximum allowable compressive stress is given by equation

$$f_c = \frac{1}{12}\frac{E}{\sqrt{3\,(1-\mu^2)}} \times \frac{(t_s - C)}{\frac{D_o}{2}} \veeeq \frac{0.15\,(t_s - C)E}{D_o}$$

Here, μ = Poisson's ratio
E= Modulus of Elasticity

If distillation column is to be operated under vacuum or if it is to be subjected to external pressure then stresses created by external pressure in circumferential direction (f_{cp}) and in axial direction (f_{ap}) are given by the same equation as for the internal pressure.

$$f_{cp} = \frac{PD_i}{2\,(t_s - C)}$$

$$f_{ap} = \frac{PD_i}{4(t_s - C)}$$

Here external pressures f_{cp} and f_{ap} are compressive in nature.

Hence, if column is subjected to external pressure then maximum tensile stress induced in shell plate in axial direction at a distance X from the top is given by equation

$$-f_{ap} - f_{dx} + f_{wx} + f_{ex} + f_{sx} = f_{tmax}$$

In the same case, maximum compressive stress induced in axial direction at a distance X from the top is given by equation.

$$f_{ap} + f_{dx} + f_{wx} + f_{ex} + f_{sx} = f_{cmax}$$

In this case also, to find the value of X, $f_{tmax}$and $f_{cmax}$are replaced by J× f_{tallow} and J × f_{callow} respectively.

Noting that stresses created by wind load, eccentric load and seismic load are tensile on one side of circumference of shell, but the same are compressive (with same value) on the opposite side of the circumference of shell. Hence in calculations of maximum compressive stress these stresses are considered as compressive stress.

II. Example

A distillation column is to be fabricated & installed, having following specifications?

Shell O.D. at top = 20000mm,
Shell length = 27m,
Internal design pressure = 3 kgf/cm^2,
Design temperature = 120˚c,
Shell material = SA – 283 Grade C,
Type of shell plate joint = Double welded butt joint with 10% Radiography,
Skirt height = 4 m,
Tray spacing (106 trays) = 0.3 m,
Top disengaging space = 1.2 m,
Weight of liquid and tray = 120 kg/m^2
Weight of attachment (pipes, ladders & platform) = 150 kg/m
Wind pressureP_w = 130 kgf/m^2
Insulation thickness t_{ins} = 100mm
Density of insulation ρ_{ins} = 500kg/m^3
Maximum allowable stress of shell plate material

At design temperature f = 890 kgf/cm^2
Modulus of Elasticity 'E' = 2*10^{6}kgf/cm^2
Poisson's ratio 'μ' = 0.3
Corrosion allowance (C.A.) = 2mm
Specific gravity of SA – 283 Gr C material = 7.865
Maximum weight of vessel, its attachment & content =300000 kg
Height of skirt =5m
Diameter of skirt =2000mm

Neglect the stress created by eccentric load & seismic load. Calculate the thickness of shell plate for entire tower.

For internal design pressure

Shell thickness

Internal design pressure = 3 kgf/cm^2
O.D. of shell at top = D_0 = 2000mm

$$t_s = \frac{PD_o}{2fJ + P} + C.A.$$

$$t_s = \frac{3 \times 2000}{2 \times 890 \times 0.85 + 3} + 2$$

$$t_s = 5.96\text{mm}$$

$D_i = D_o - 2t_s$
$D_i = 2000 - 2(5.96)$
$D_i = 1987.3\text{mm}$

Design of head:

$$t'_h = \frac{PR_cW}{2fJ - 0.2P} + C.A.$$

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

$R_c = D_i = 1987.3\text{mm}$
$R_k = 0.1 \times R_c = 198.73\text{mm}$

$$W = \frac{1}{4}\left[3 + \sqrt{\frac{1987.3}{198.73}}\right]$$

$$W = 1.54$$

$$t'_h = \frac{3 \times 1987.3 \times 1.54}{2 \times 890 \times 0.85 - 0.2 \times 3} + 2$$

$$t'_h = 8.07\text{mm}$$
$$t_h = 1.06 \times t'_h$$
$$t_h = 8.55\text{ mm}$$

$$\text{Blank daimeter} = \text{O.D.} + \frac{\text{O.D.}}{42} + \frac{2}{3}i_{cr} + 2SF \quad (\text{for } t_h \leq 1")$$

O.D. = 1987.3 + 20=2007.3mm
SF =1.5”=38.1mm

$$\text{Blank daimeter} = 2007.3 + \frac{20007.3}{42} + \frac{2}{3} \times 1987.73 + 2 \times 38.1 \quad (\text{for } t_h \leq 1")$$

$$\text{Blank daimeter} = 2263.78\text{mm}$$

$$\text{Weight of head} = \frac{\pi}{4} \times (2.26378)^2 \times 0.01 \times 7865$$
$$\text{Weight of head} = 316.56\text{ kg}$$

Volume of head=0.000049$(D_i)^3 + \frac{\pi}{4} \times D_i^2 \times SF \times \rho$ = 925.73 m^3

Let X be the distance from the top of up to which we can use 6.35mm thick shell

(A) Circumferential stress induced in shell plate material at a distance X from the top of shell (due to internal pressure)

$$f_{cp} = \frac{PD_i}{2(t_s - CA)}$$

$$f_{cp} = \frac{3 \times 198.73}{2(0.635 - 0.2)}$$

$$f_{cp} = 685.275 \text{ kgf/cm}^2$$

$$J \times f_{tallow} = 0.85 \times 890 = 756.5 \text{ kgf/cm}^2$$

$$f_{cp} < 0.85 \ f_{tallow}$$

f_{cp} will remain same for entire length.

(B) Various axial stresses induced due to internal in the shell plate material at a distance X from the top of the shell.

I. Axial stress induced due to internal pressure

$$f_{ap} = \frac{PD_i}{4(t_s - CA)}$$

$$f_{ap} = \frac{3 \times 198.73}{4(0.635 - 0.2)}$$

$$f_{ap} = 342.63 \text{ kgf/cm}^2$$

II. Axial stress induced due to dead load

$$f_{dx} = f_{dsx} + f_{d(ins)x} + f_{d(liq)x} + f_{d(att)x}$$

Where f_{dsx} = stress induced due to the wt. of shell

$$f_{dsx} = \frac{\frac{\pi}{4}(Do^2 - Di^2)\rho_s X \frac{g}{g_c}}{\pi D_m (t_s - C)} \cong \rho_s \frac{g}{g_c} X$$

$$f_{dsx} = \rho_s \frac{g}{g_c} X$$

$$f_{dsx} = 7865 \times X \text{ kgf/m}^2$$

$$f_{dsx} = 0.7865 \times X \text{ kgf/cm}^2$$

$$f_{d(ins)x} = \frac{\pi D_{ins} t_{ins} \rho_{ins} X \frac{g}{g_c}}{\pi D_m (t_s - C)}$$

$$D_m = \frac{D_o + D_i}{2}$$

$$D_m = \frac{2000 + 1987.3}{2}$$

$$D_m = 1993.65 \ mm$$

$$D_{ins} = D_o + t_{ins}$$

$$D_{ins} = 2100 \ mm$$

$$f_{d(ins)x} = \frac{\pi \times 2100 \times 100 \times 500X}{\pi \times 1993.65(6.35 - 2)}$$

$$f_{d(ins)x} = 1.21074 \text{ X kgf/cm}^2$$

$$\mathrm{f}_{d(liq.+tray)} = \frac{F_{liq+tray)}}{\pi D_m(t_s - C)}$$

$$F_{(liq+tray)X} = (\frac{X - h_1}{S} + 1) \times \frac{\pi}{4} Di^2 \times (wt.ofonetrayperunitarea + wt.liquidoveronetrayperunitarea)$$

$$F_{(liq+tray)X} = (\frac{\mathrm{X} - 1.2}{0.3} + 1) \times \frac{\pi}{4} \times (1.9873)^2 \times 120$$

$$F_{(liq+tray)X} = 1240.73\,(X - 0.9) kgf$$

$$\mathrm{f}_{d(liq.+tray)} = \frac{1240.73\,(X - 0.9)}{\pi \times 1.99365(6.35 - 2) \times 10^{-3}}$$

$$\mathrm{f}_{d(liq.+tray)} = [4.55396X - 4.09856]\mathrm{kgf/cm^2}\ (\mathrm{whereXinm})$$

$$f_{d(att)} = \frac{\sum wieghtofattachmentperunitheightX}{\pi D_m(t_s - C)}$$

$$f_{d(att)} = \frac{316.56 + 150X}{\pi \times 1.99365\,(6.35 - 2) \times 10^{-3}}$$

$$f_{d(att)} = 1.161898 + 0.55056\,X\ \mathrm{kgf/cm^2}$$

Total axial compressive stress induced due to dead loads

$$\mathrm{f_{dx}} = 0.7865\,\mathrm{X} + 1.21074\,\mathrm{X} + 4.55396\,\mathrm{X} - 4.09856 + 1.161898 + 0.55056\,\mathrm{X}$$

$$\mathrm{f_{dx}} = 7.10176\,\mathrm{X} - 2.93666$$

III. Axial stress induced due to wind load at a distance X from the top of the shell

$$f_{wx} = \frac{1.4\,P_w D_o X^2}{\pi Do^2\,(t_s - C)} = \frac{1.4 P_w X^2}{\pi D_o\,(t_s - C)}$$

$$f_{wx} = \frac{1.4 \times 130\,X^2}{\pi \times 2 \times\ (6.35 - 2) \times 10^{-3}}$$

$$f_{wx} = 0.66589\,X^2 \mathrm{kgf/cm^2}$$

Maximum tensile stress induced in the shell plate material at a distance X from the top of the shell.

$$f_{wx} + f_{ap} - f_{dx} = f_{tmax}$$

$$0.66589\,X^2 - 7.10176\,X + 2.93666 + 342.63 = 0.85\ \times 890$$

$$0.66589\,X^2 - 7.10176\ - 410.93 = 0$$

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

$$x = \frac{7.10176 \pm \sqrt{7.10176^2 - 4 \times 0.66589 \times (-410.93)}}{2 \times 0.66589}$$

$$x = 30.74\,\mathrm{m}$$

Maximum compressive stress induced in the shell plate at a distance X from the top of the shell

$$f_{cmax} = f_{wx} + f_{dx} - f_{ap}$$

$$f_{callow} = \frac{1}{12} \frac{E}{\sqrt{3\,(1 - \mu^2)}} \times \frac{(t_s - C)}{\frac{D_o}{2}}$$

$$f_{callow} = \frac{1}{12} \frac{2 \times 10^6}{\sqrt{3\,(1 - 0.3^2)}} \times \frac{(6.35 - 2)}{\frac{2000}{2}}$$

$$f_{callow} = 438.79 \mathrm{kgf/cm^2}$$

$$0.85 \times 438.79 = 0.66589\,X^2 + 7.10176\,X - 2.93666 - 342.63$$
$$0.66589\,X^2 + 7.10176\,X - 718.538 = 0$$

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$
$$x = \frac{-7.10176 \pm \sqrt{(7.10176)^2 - 4 \times 0.66589 \times 718.538}}{2 \times 0.66589}$$
$$x = 27.9466\ \mathrm{m}$$

Up to 27.5 m keep thickness of shell equal to 6.35 mm.

Weight of tower $= \frac{\pi}{4}\,(D_o - D_i) \times t_s \times \rho_m = 8765.44$ kg

Design of skirt support:

(a) Determination of the thickness of skirt:

I. Stress created due to dead load

$$f_{db} = \frac{\sum W}{\pi\, D_{ok}\, t_{sk}}$$

$$f_{db} = \frac{300000}{\pi \times 200 t_{sk}}$$

$$f_{db} = \frac{477.46}{t_{sk}}\ \mathrm{Kgf/cm^2}$$

II. Stress created due to wind load

$$f_{wb} = \frac{M_{wb}}{Z}$$

Where,

$$M_{wb} = \frac{0.7\, P_1\, h_1{}^2 D_o}{2} + 0.7\, P_2 D_o h_2 \left(h_1 + \frac{h_2}{2}\right)$$
$$h_1 = 20\mathrm{m}, \qquad H = 27\mathrm{m} + 5\mathrm{m}$$

$$h_2 = 12\mathrm{m}$$

$$M_{wb} = \frac{0.7 \times 100 \times 20^2 \times 2}{2} + 0.7 \times 128.5 \times 2 \times 12 \left(20 + \frac{12}{2}\right)$$
$$M_{wb} = 84128.8\ \mathrm{kgf.m}$$

$$f_{wb} = \frac{84128.8 \times 100}{\frac{\pi}{4} \times (250)^2 \times t_{sk}}$$

$$f_{wb} = \frac{171.38}{t_{sk}}\ \mathrm{Kgf/cm^2}$$

III. Stress Created due to seismic load

$$f_{sb} = \frac{M_{sb}}{Z} = \frac{\frac{2}{3}\,\mathrm{CHW}}{\frac{\pi}{4} \times D_{ok}{}^2\, t_{sk}}$$

$$M_{sb} = \frac{2}{3}\,\mathrm{CHW}$$

$$M_{sb} = \frac{2}{3} \times 0.08 \times 300000 \times 32$$

$$M_{sb} = 512000 \text{ kgf.m}$$

$$f_{sb} = \frac{M_{sb}}{Z} = \frac{512000 \times 100}{\frac{\pi}{4} \times 200^2 \, t_{sk}}$$

$$f_{sb} = \frac{1629.74}{t_{sk}} \text{ Kgf/cm}^2$$

$$f_{sb} > f_{wb}$$

Maximum tensile stress

$$f_{tmax} = f_{sb} - f_{db} = \frac{1629.47}{t_{sk}} - \frac{477.46}{t_{sk}}$$

$$f_{tmax} = \frac{1152.28}{t_{sk}}$$

Let, $f_{tmax} = Jf_{tallow} = 1400 \times 0.85 = 1190 \text{ Kgf/cm}^2$

$$t_{sk} = \frac{1152.28}{1190}$$

$$t_{sk} = 0.9683\text{cm} = 9.683\text{mm}$$

Maximum compressive stress

$$f_{cmax} = f_{sb} + f_{db}$$

$$f_{callow} J = f_{sb} + f_{db} = \frac{1629.47}{t_{sk}} + \frac{477.46}{t_{sk}}$$

$$666 \times 0.85 = \frac{2106.93}{t_{sk}}$$

$$t_{sk} = 3.72\text{cm} = 37.22\text{mm}$$

Use 38mm thick plate for the fabrication of shell for skirt support

(b) Bearing plate design:

Outer diameter of bearing plate
=Shell O.D. + 30cm = 200 + 30 = 230cm

Compressive stress induced in bearing plate & on concrete foundation

$$F_{cmax} = \frac{\sum W}{A} + \frac{M_{wb} \text{ or } M_{sb}}{Z}$$

(Weight of skirt = $\pi \times 2 \times 0.038 \times 5 \times 8000 = 9550.44 \cong 9600kg$)

$$\sum W = 300000 + 9600 = 309600 \; kg$$

$$A = \frac{\pi}{4} \times (230^2 - 200^2) = 10131.64 \; cm^2$$

$$M_{sb} = 512000\ kgf.m > M_{wb}$$

$$Z = \frac{\pi}{32} \times \frac{(D_o{}^4 - D_i{}^4)}{D_o} = \frac{\pi}{32} \times \frac{(230^4 - 200^4)}{230}$$

$$Z = 511537.57\ cm^3$$

$$F_{cmax} = \frac{309600}{10131.64} + \frac{512000 \times 100}{511537.57}$$

$$F_{cmax} = 130.64 > 35\ Kgf/cm^2$$

Outer diameter of bearing plate
=Shell O.D. + 30cm = 200 + 100 = 300 cm

$$A = \frac{\pi}{4} \times (300^2 - 200^2) = 39269.91\ cm^2$$

$$Z = \frac{\pi}{32} \times \frac{(D_o{}^4 - D_i{}^4)}{D_o} = \frac{\pi}{32} \times \frac{(300^4 - 200^4)}{300} = 2127120.026\ cm^3$$

$$F_{cmax} = \frac{309600}{39269.91} + \frac{512000 \times 100}{2127120.026}$$

$$F_{cmax} = 31.95 < 35\ Kgf/cm^2$$

Induced compressive stress in the concrete is less than maximum allowable stress.

Use bearing plate having 3000mm O.D. & 2000mm I.D.

(c) Thickness of bearing plate

$$t_B = \sqrt{\frac{3\ f_{cmax}\ l^2}{f}}$$

$$l = \frac{300 - 200}{2} = 50cm$$

$$f_{cmax} = 1575\ Kgf/cm^2$$

$$t_B = \sqrt{\frac{3 \times 31.94 \times 50^2}{1575}}$$

$$t_B = 12.33\ cm = 123.32\ mm$$

Use 124mm thick bearing plate
$t_B > 18mm\ so, bolting\ chair\ required$

Bolt design:

Maximum compressive stress induced in bearing plate

$$f_{cmin} = \frac{M_{min}}{A} - \frac{M_{wb}\ or\ M_{sb}}{Z}$$

O.D. of bearing plate = 200 + 100 = 300 cm

$$A = \frac{\pi}{4} \times (300^2 - 200^2) = 39269.91\, cm^2$$

$$Z = \frac{\pi}{32} \times \frac{({D_o}^4 - {D_i}^4)}{D_o} = \frac{\pi}{32} \times \frac{(300^4 - 200^4)}{300} = 2127120.026\, cm^3$$

$$f_{cmin} = \frac{309600}{39269.91} - \frac{512000 \times 100}{2127120.026}$$

$$f_{cmin} = -16.18\, kgf/cm^2$$

$$f_{cmax} = \frac{M_{min}}{A} + \frac{M_{wb}\ or\ M_{sb}}{Z}$$

$$f_{cmax} = 31.95\, kgf/cm^2$$

Anchor bolts must be used

Use centred type bolting chair

$$Minimum\ no\ of\ bolt\ requred = \frac{D}{600} = \frac{2000}{600} = 3.34$$

Maximum no’s of bolts

Skirt diameter = 2500mm = 8.2ft
Maximum No’s of bolts = 16
Use 8 no’s of centred type bolting chair
Load on each bolt

$$P_{bolt} = f_{cmin} \frac{A}{n} = \frac{16.18 \times 39269.91}{16}$$

$$P_{bolt} = 39711.69\, kgf$$

Maximum allowable tensile stress of bolt material

$$f = 1020.7\, kgf/cm^2$$

Area of bolt required

$$A_b = \frac{p_b}{f} = \frac{39711.69}{1020.7} = 38.91 cm^2$$

$$Bolt\ daimeter = \sqrt{\frac{4 \times 38.91}{\pi}} = 7.03 cm \cong 72 mm$$

Use 16 No’s of bolting chairs & Use 72mm size bolts

Thickness of bearing plate inside the bolting chair

$$t_{BP} = \frac{\sqrt{6 \times M_{max}}}{\sqrt{(W_{BP} - d_{bhd}) \times f_{allow}}}$$

$$b = spacing\ between\ stiffeners = 203.0 mm$$

$$M_{max} = \frac{39711.69 \times 20.32}{7.2}$$

M_{max} = 112075.21 $kgf.cm$

W_{BP} = $width\ of\ bearing\ plate$ = 50cm

d_{bhd} = 8.2 cm
f_{allow} = 1400kgf/cm^2
t_{BP} = 2.96cm = 29.6mm < 124mm

We can keep 124mm thickness of bearing plate uniform throughout.

Nozzle design:
Area for area method:

Area for which compensation is required is given by;

A =$t_s \times d_i$=6.35 × 218 = 1384.3mm^2

Where, d_i= inside diameter of nozzle pipe

t_s= thickness of shell, head or jacket or minimum thickness required by shell, jacket or head or head on which nozzle is to be provide

AB = 4ri = 2di = horizontal limit for reinforcement

t'_n = 7.793mm

H1 = 2.5t_n=2.5*16=40 mm

H1 = vertical limit for reinforcement, measured from surface of reinforcement pad or of the shell.

H1 = 2.5 t_n = $\sqrt{(d_i + 2c)(t_n - c)}$

t_n= actual thickness of nozzle, if the compensation is to be provided by combination of nozzle & reinforcement pad. If compensation is not provided than,

$A = A_i + A_o + A_s$

Area available for compensation is expressed as,

(1) Compensation provided by additional thickness of shell or head
A_s= $d_i(t_s - t'_s - c)$=218(8-6.35) = 359.7mm^2
(2) Compensation provided by additional thickness of nozzle external to the vessel

A_n= 2.5$H_1(t_n - t'_n - c)$=40*2.5(4-2.9) = 110mm^2

Additional compensation area required:

A_R= A-($A_n + A_{s)}$=3184.3-(359.7+110) = 2714.6mm^2

Where, t'_s = actual thickness of shell, head or nozzle.

t_n = calculated minimum thickness of nozzle

t'_s = theoretical minimum calculated thickness

c = corrosion allowance

A_R = (D – d_o) t = (2*218-250) = 186mm^2

$(D_{or} - D_{ir})\, t_R$ = 186

t_R = 3.5mm

Where, D = O.D. of reinforcement pad

t = thickness of reinforcement pad
d_o = O.D. of the nozzle pipe
Weight of nozzle $= \frac{\pi}{4}\left({D_{or}}^2 - {D_{ir}}^2\right) \times \rho \times t_R$ = 31.6kg

Summary:

Shell thickness = 6mm
Head Thickness = 10mm
Weight of Head = 316.56kg
Tower Thickness = 6.35mm
Skirt thickness = 38mm
Bolt diameter = 72mm
Centre type bolting chair = 8
Anchor type bolt = 16
Nozzle thickness = 2.9mm
Weight of nozzle = 31.9 kg
Bearing plate thickness = 124mm
Outer diameter = 3000mm
Inner diameter = 2000mm
Volume of the Head = 925.73 m^3
Weight of tower = 8765.44 kg

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