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Design of Vertical Pressure Vessel using PV Elite software

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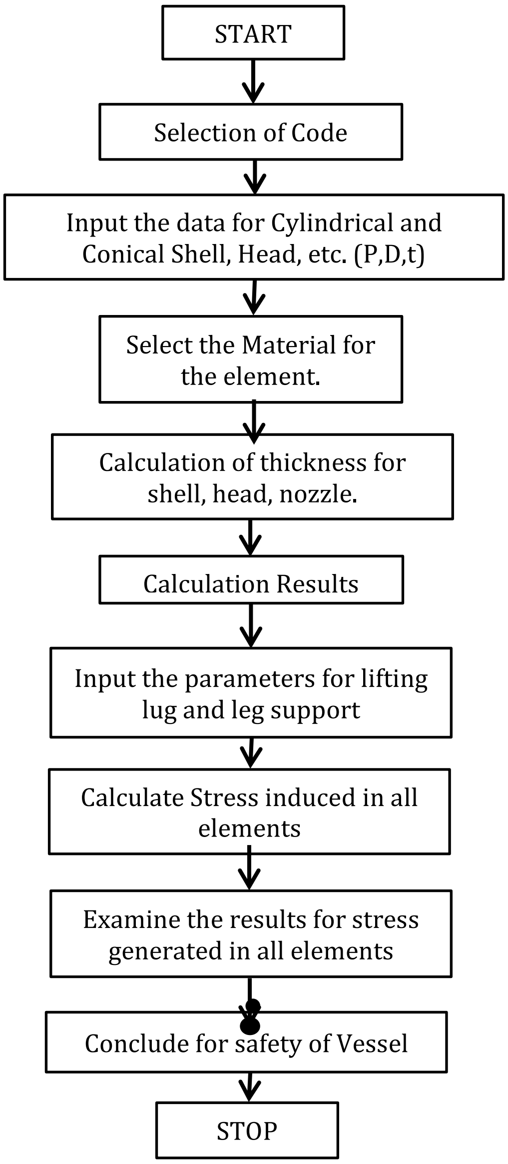
Abstract – *Pressure Vessel is an important part of many industries such as chemical industries, oil and gas industry, marine applications, power industry. A pressure vessel is a container used to store fluids, gases and substances at a pressure more or less than the atmospheric pressure. Pressure vessels are used to store toxic gases, cryogenic substances, chemicals, water and steam at extremely high or low temperatures. The pressure differential causes bursting of pressure vessel which is hazardous to people working around and also a big loss for the industry. Therefore the design of pressure vessel is critical and standard codes are required to be used for the design purpose. For the industries based on pressure vessel design and manufacturing softwares are developed which eliminate the hectic task of doing analytical calculations. The softwares have the standard codes embedded in them and work on the pressure vessel design according to the design criteria and standard formulae given in the codes. PV Elite is one such software developed by Integraph for design of vessels. The results obtained by using the software are reliable, accurate and more promising than the analytical calculations done by the engineers.*

Key Words: Design, PV Elite, standard codes, accurate results.

1. INTRODUCTION

Integraph PV Elite is a complete solution for vessel design design and heat exchanger design, analysis and evaluation. User can quickly design the equipment for the most extreme cases and get accurate results profitably. The software has data of standard Pressure vessel design codes such as ASME Division 1 and Division 2, EN 13445 code, PD 5500 along with the material database which includes all the data of all materials used for the vessel. Other data such as piping and steel component data, local wind loads and seismic loads of many regional markets. The software has preset data of all the elements and details required in a vessel. The software takes the inputs from the user about the elements and details of the vessel and converts the input data into actual model of the vessel. The inputs are based on the requirements of the user, experience of the user in vessel design and may change depending on the applications. PV Elite includes CodeCalc for quick and accurate component design and evaluation. The outputs are processed in terms of parameters such as required thickness, maximum allowable working pressure and also by type such as internal and external pressure, bending stress, nozzle and flanges. The overall results are summarized whether the vessel sustains the applied pressure and the overall maximum working allowable pressure (MAWP) is identified.

The following flowchart describes the steps for solving the pressure vessel problem.



1.1 PROBLEM STATEMENT

Design of vertical pressure vessel of 1500mm diameter and subjected to internal pressure of 5 bar for constant supply of fluid (paper pulp + water) for headbox machine in paper industry.

1.2 INPUT DATA

I. Maximum Allowable Pressure and Temperature = 5 bar and 60°C.
II. Minimum Allowable Pressure and Temperature = 2.5 bar and -29°C.
III. Volume of Pressure Equipment = 4.1 m^3
IV. Test pressure applied = 8.2 bar
V. Fluid group =2 (Paper pulp + water)
VI. Vessel diameter = 1500mm

1.3 CODE SELECTION

The code selection is based on the region in which the vessel is to be installed. The region defines the standard code to be used. The ASME codes are used for American region, EN-13445 is used in European nations, PD 5500 also used in European nations, IS 2825 used in India. All the codes give the approximately same results. The codes are developed from experimental results for different types of conditions. The factor of safety considered in the codes is 3.5 to 4 for unfired pressure vessels. Selecting EN-13445 code for Unfired Pressure Vessel as per our requirement.

2. MATERIAL SELECTION

A variety of material are available for the manufacturing of pressure vessels. Some of the materials are gray Cast Iron, stainless steel, cast steel, alloy steel, aluminium, composites. The material is selected from EN-13445 part-2 – Materials. Selecting Cr-Mo steels free of Vanadium with C < 0.35%. Selecting material X2CrNiMo 17-12-2 Material Number 1.4404, Tm = -196°C. Allowable stress for the material at design temperature $\sigma_{all} = 160\ N/mm^2$. The material is selected due to following reasons:
1. High corrosion and pitting resistance of the material.
2. High strength of material compared to other materials.
One can vary the material used according to their application and cost considerations.

3. MODELLING OF VESSEL IN PV ELITE

The vessel is modeled from bottom to top as shown in fig. The elements are added based on pre-calculations done on basis of total volume and required structure. By trail and error method the volume of each element when added should give the total volume. We have selected cylindrical shell with elliptical head and two converging cones at bottom such that the bottom cone inlet diameter is equal to diameter of pipe.
First calculate required thickness of shell using thickness formula from EN-13345 Part 3 Design
t = (P*Di)/(2*σ*z –P) = (0.5*1500)/(2*160*1-0.5) =2.34mm.
Selecting 5mm thickness of stainless steel plate for all elements as per availability of material.

Element 1:
Cylindrical Shell: Inner Diameter=600mm, length =250mm, thickness = 5mm, Material- X2CrNiMo 17-12-2, Internal Pressure = 50kPa, Temperature for internal Pressure = 60°C. This element is as reference of inlet fluid pipe connecting the vessel.

Element 2 and 3:
Body Flange: Inner Diameter=600mm, flange length =25mm, finished thickness = 25mm, Material- X2CrNiMo 17-12-2, Internal Pressure = 50kPa, Temperature for internal Pressure = 60°C. The flange is a loose plate type flange used to connect inlet pipe and the vessel.

Element 4:
Cylindrical Shell: Inner Diameter=600mm, length =50mm, thickness = 5mm, Material- X2CrNiMo 17-12-2, Internal Pressure = 50kPa, Temperature for internal Pressure = 60°C. this element is provided to avoid abrupt changes due to conical element to be connected.

Element 5:
Conical Shell: From end diameter = 600m, cone length = 550mm, to end inside diameter= 760mm, thickness = 5mm, Material- X-2CrNiMo 17-12-2, Internal Pressure = 50kPa, Temperature for internal Pressure = 60°C, Longitudinal and joint efficiency =1. Volume of cone1= 0.2m^3.

Element 6:
Conical Shell: From end diameter = 760m, cone length = 760mm, to end inside diameter= 1500mm, thickness = 5mm, Material- X2CrNiMo 17-12-2, Internal Pressure = 50kPa, Temperature for internal Pressure = 60°C, Longitudinal and joint efficiency =1. Volume of cone2= 0.79m^3.

Element 8:
Cylindrical Shell: Inner Diameter=1500mm, length =130mm, thickness = 5mm, Material- X2CrNiMo 17-12-2, Internal Pressure = 50kPa, Temperature for internal Pressure = 60°C. Volume = 0.229m^3.

Element 9 and 10:
Body Flange: Inner Diameter=1500mm, flange length =65mm, finished thickness = 65mm, Material- X2CrNiMo

17-12-2, Internal Pressure = 50kPa, Temperature for internal Pressure = 60°C. The flange is a loose plate type flange used to connect inlet pipe and the vessel. These flanges are used to connect the conical shell and cylindrical shell. Volume contained =0.229m^3.

Element 11:
Cylindrical Shell: Inner Diameter=1500mm, length =1500mm, thickness = 5mm, Material- X2CrNiMo 17-12-2, Internal Pressure = 50kPa, Temperature for internal Pressure = 60°C. Volume = 2.65m^3.

Element 12:
Elliptical Head: Inside Diameter=1500mm, straight flange length =50mm, thickness = 5mm, Material- X2CrNiMo 17-12-2, Internal Pressure = 50kPa, Temperature for internal Pressure = 60°C. Volume = 0.46m^3.

Nozzle Data:
Enter nozzle data in nozzle element information. The nozzle is selected without reinforcement and if it fails then nozzle with reinforcement is to be selected. The nozzle information will vary according to the requirements of the consumer.

i. **Manhole:** Manhole is provided for cleaning and maintenance of vessel. Following Inputs are required Nozzle Material- X2CrNiMo 17-12-2, Nozzle diameter (ID)= 500mm, thickness= 5mm, Projection Outside = 150mm, Nozzle to shell outside fillet weld leg=10mm, remaining data can be kept standard.

ii. **Nozzle 2**: This nozzle can be used for any instrument connection. Nozzle Material- X2CrNiMo 17-12-2, Nozzle diameter (ID)= 50mm, thickness= 5mm, Projection Outside = 150mm, Offset dimension= 600 mm, Layout angle = 210°. Nozzle to shell outside fillet weld leg=10mm, remaining data can be kept standard.

iii. **Nozzle 3**: This nozzle can be used for any instrument connection. Nozzle Material- X2CrNiMo 17-12-2, Nozzle diameter (ID)= 65mm, thickness= 5mm, Projection Outside = 150mm, Offset dimension= 600 mm, Layout angle = 180°. Nozzle to shell outside fillet weld leg=10mm, remaining data can be kept standard.

iv. **Nozzle 4**: This nozzle can be used for fusible plug. Nozzle Material- X2CrNiMo 17-12-2, Nozzle diameter (ID)= 65mm, thickness= 5mm, Projection Outside = 150mm, Offset dimension= 600 mm, Layout angle = 330°. Nozzle to shell outside fillet weld leg=10mm, remaining data can be kept standard.

v. **Outlet Nozzle:** The inputs given are as follows: Nozzle Material- X2CrNiMo 17-12-2, Nozzle diameter (ID)= 900mm, thickness= 8.8mm, Projection Outside = 150mm, Offset dimension= 600 mm, Layout angle = 90°, distance from node: Elevation=492.37, 2430mm. Nozzle to shell outside fillet weld leg=10mm, remaining data can be kept standard.

Details of LUG Support:
From Node = 60
Distance from node = 500mm
Lug Material = X2CrNiMo 17-12
No of leg = 4
Perform WRC 107 Calculation to find the required details.

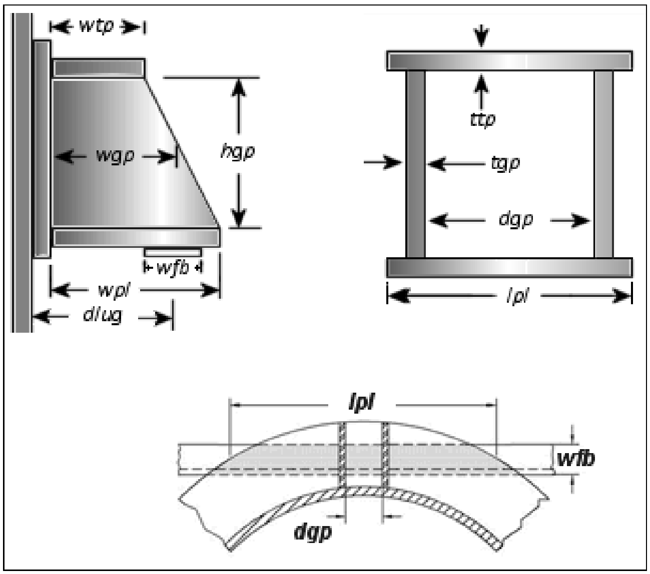


Fig.- 1: Details of Lug Support

Details of Lifting Lug:
From Node= 100
Distance from node = 1500mm
Lug Contact Width(w) = 200mm
Diameter of hole in lug(dh) = 50mm
Radius of semicircular arc(r)=80mm
Lug Material = X2CrNiMo17-12
Lug thickness = 14mm
Offest from vessel OD to Centre of the hole(off) = 8mm
Height from bottom to centre of hole(h)=300mm
Length of weld along side of lifting lug(wl) = 80mm
Length of weld along bottom of Lifting lug(wb)= 130mm

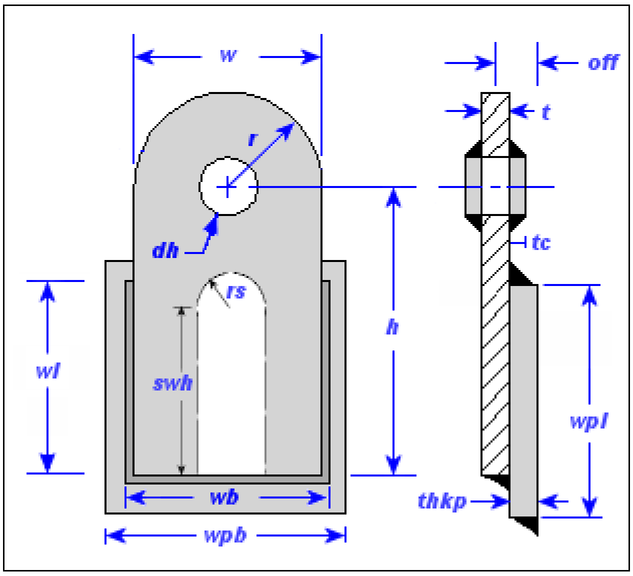


Fig.-2: Details of Lifting Lug

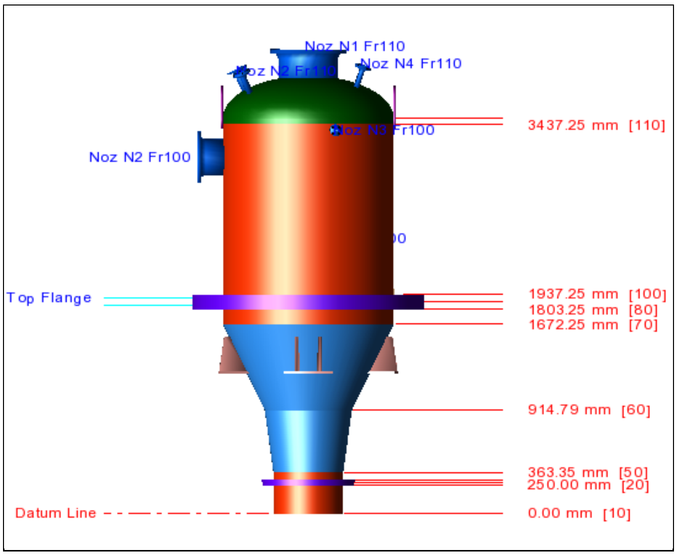


Fig.-3: PV Elite Model of the Vessel.(Front view)

4. DESIGN CALCULATIONS AND RESULTS

The calculations and results are obtained from analyse option in the software.

4.1 Lower cone calculations:

Design Stress at Ambient Temperature = 180.006 N/mm^2
Thickness Due to Design Internal Pressure: e - para 7.5.2
t= ((P * Dica) / (2 * f * z - P)) * (1/Cosa) Eqn 7.6-2
= ((78.87*760.00)/(2*160.01*1.00-78.87))*(1/0.99)
= 0.1892 + 0.0000 + 0.0000 = 0.1892 mm

The cone is suitable for the design pressure

Maximum Allowable Working Pressure at Given Thickness [Pmax]:Less Operating Hydrostatic Head Pressure of 28.87 kPa = (2 * f * z * ecor * Cosa) / (Dica + (ecor * Cosa)) [MAWP]
=(2*160.01*1.00*5.00)/(0.99+(760.00*5.00))-Phead
= 2071.27 - 28.87 = 2042.39 kPa.

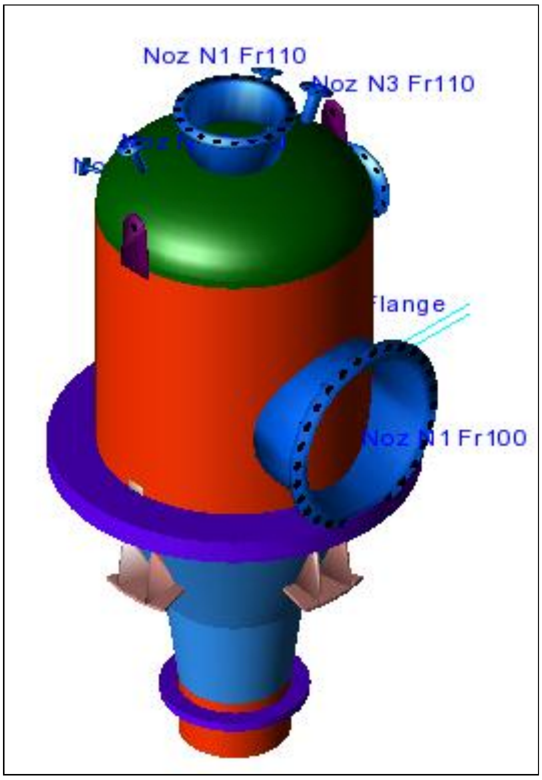


Fig.-4: Isometric View of the Vessel.

Actual Stress at Given Thickness [Stress]:
= (P * Dica / (2 * ecor * cos(angle)) [Stress]
= (78.87*760.00)/(2*5.0000*0.9903)
= 6.05 N/mm^2

The stress developed is 6.05N/ mm^2 which is less than the allowable stress of the selected material (160N/mm^2). Hence the cone is safe.

4.2 Upper cone Calculations:

Thickness Due to Design Internal Pressure: e - para 7.5.2
= ((P * Dica) / (2 * f * z - P)) * (1/Cosa) Eqn 7.6-2
=((71.45*1500.00)/(2*160.01*1.0071.45))*(1/0.90)
= 0.3728 + 0.0000 + 0.0000 = 0.3728 mm

The cone is suitable for the design pressure

Maximum Allowable Working Pressure at Given Thickness [Pmax]:Less Operating Hydrostatic Head Pressure of 21.45 kPa
= (2 * f * z * ecor * Cosa) / (Dica + (ecor * Cosa)) [MAWP]
=(2*160.01*1.00*5.00)/(0.90+(1500.00*5.00))-Phead

= 955.60 - 21.45 = 934.15 kPa

Actual Stress at Given Thickness [Stres]:
= (P * Dica / (2 * ecor * cos(angle)) [Stres]
= (71.45*1500.00)/(2*5.0000*0.8986)
= 11.93 N/mm^2.

The stress developed is 11.93 N/ mm^2 which is less than the allowable stress of the selected material (160N/mm^2). Hence the cone is safe.

4.3 Cylindrical Shell (Element 11) Calculations:

Thickness due to internal pressure [e]:
= P * Di / (2 * f * z - P) EN13445 Equation: 7.4.2:
= 71.45 * 1500.00/(2 * 160.008 * 1.000 - 0.071) + c + cext
= 0.3350 + 0.0000 + 0.0000 = 0.3350 mm

The shell is suitable for the design pressure.

Maximum Working Pressure Hot and Corroded [MAWP]:
= (2 * f * ecor * z) / (Di + ecor) - Phead
= (2 * 160.01 * 5.0000 * 1.000)/(1500.00 + 5.0000)-21.45 = 1.042 N/mm^2

Stress at Design Pressure [Stres]:
= P(Di + ecor) /(2 * ecor * z)
= 71.453 (1500.000 + 5.0000)/(2 * 5.0000 * 1.000)
= 10.754 N/mm^2.

The stress developed is 10.75N/ mm^2 which is less than the allowable stress of the selected material (160N/mm^2). Hence the shell is safe.

4.4 Cylindrical Shell (Element 11) Calculations:

Thickness due to internal pressure [e]:
= P * Di / (2 * f * z - P) EN13445 Equation: 7.4.2:
= 68.86 * 1500.00/(2 * 160.008 * 1.000 -0.069) + c + cext
= 0.3228 + 0.0000 + 0.0000 = 0.3228 mm

The shell is suitable for the design pressure.

Maximum Working Pressure Hot and Corroded [MAWP]:
= (2 * f * ecor * z) / (Di + ecor) - Phead
= (2 * 160.01 * 5.0000 * 1.000)/(1500.00 + 5.0000)-18.86 = 1.044 N/mm^2

Stress at Design Pressure [Stress]:
= P(Di + ecor) /(2 * ecor * z)
= 68.857 (1500.000 + 5.0000)/(2 * 5.0000 * 1.000)
= 10.364 N/mm^2

The stress developed is 10.36N/ mm^2 which is less than the allowable stress of the selected material (160N/mm^2). Hence the shell is safe.

4.5 Ellipsoidal Shell (Element 12) Calculations:

Required thickness = 0.813 mm
Required thickness in the crown = 0.226 mm

Note: This head has a nozzle located outside the 80% diameter limit. This modifies the value of Beta (Beta_k) per paragraph 7.7.3.

The Material is Austenitic Steel which affects value of fb:

Buckling Strs at ope. fb = Yield/1.5 = 203.035/1.5 = 135.357 N/mm^2
Buckling Strs at amb. fb = Yield/1.5 = 278.290/1.5 = 185.527 N/mm^2

Note: Although head is Austenititic Steel, Rp0,20% is used.

Ellipsoidal head find geometry for equiv. tori-head EN 13445 Equation 7.5.4:

Pressure including hydro head P : 53.673 kPa
Inside Head Diameter(new)Di : 1500.0000 mm
Head Thickness(new)e : 5.0000 mm
Head Aspect Ratio(new)Di/2h : 2.0000
Head Corrosion Allowance Internal ci :0.0mm
Head Corrosion Allowance External co : 0.0mm
Joint Efficiency Z : 1.0000

hi = 0.5 * Di/AR + c = 0.5 * 1500.00/2.000 + 0.00 = 375.0000 mm
K = Di / (2 * hi) = 1500.000 / (2 * 375.0) = 2
r = Di((0.5 / K) - 0.08) = 1500.000((0.5/2.000)-0.08)
= 255.0000 mm
R = Di(0.44*K + 0.02) = 1500.000 (0.44*2.000 + 0.02)
= 1350.0000 mm

The nozzle is outside the 80% limit:
Nozzle corroded inside Diameter di: 57.0 mm

Y = min(e/R, 0.04) = Min(0.81284/1350.0000, 0.04) = 0.0006021
Z = Log10(1 / Y) = Log10(1 / 0.001) = 3.2203
X = r / Di = 255.0000 / 1500.0000 = 0.17000 N = 1.006 - 1 / (6.2+(90 * Y)^4))= 1.006-1 / (6.2+(90 *0.0006)^4) =0.84471

Beta01 = N(-0.1833*Z^3 + 1.0383*Z^2 - 1.2943*Z + 0.837)=0.845(-.1833*3.220^3 + 2.2124*3.220^2 - 3.2937*3.220 + 1.8873)= 1.1108
Beta02 = max (0.95 * (0.56 - 1.94 * Y - 82.5 * Y^2), 0.5)
= max (0.95 * (0.56 - 1.94 * 0.001 - 82.5 * 0.001^2), 0.5)
= 0.5309

Beta = 10((0.2 - X) * Bets01 + (X - 0.1)Beta02= 10((0.2 - 0.1700) * 1.1108 + (0.1700 - 0.1)0.5309= 0.7049

Thickness Due to Design Internal Pressure: e = max(es, ey, eb) - para 7.5.3.2

Compute from Section 7.7.3 [Beta_k]:
V = Log10(1000 * P / S)
= Log10(1000 * 53.673/160.008) = -0.4744

Note: Compute Beta_K using the Korbbogen equations.

$A = 0.54 + 0.41 * V - 0.044 * V^3$
$= 0.54 + 0.41 * -0.474 - 0.044 * -0.474^3 = 0.3502$
$B = 7.77 - 4.53 * V + 0.744 * V^2$
$= 7.77 - 4.53 * -0.474 + 0.744 * -0.474^2 = 10.0863$
Beta_k = max (A + B * di/De, 1.0 + 0.5 * B * di/De)= max (0.350 + 10.086 * 57.000/1510.000 , 1.0 +0.3 * @3 * @3/@3) = @4

Thickness Due to Design Internal Pressure: e = max(es, ey, eb) - para 7.5.3.2

Required Crown Thickness due to Internal Pressure, see Figure 7.5-3 [es]:
= P * R/(2 * f * z - 0.5 * P)
= 53.673 * 1350.0/(2 * 159998.938 * 1.00 - 0.5 * 53.673)
= 0.2265 mm

Computed Thickness [eb]
=(0.75R+0.2Di)((P/111*fb)*(Di/r)^(0.825))^(1/1.5)
=(0.75*1350.00+0.2*1500.00)*(53.67/111*135.36)(150000/255.00)^(0.825))^(1/1.5)
= 0.8128 mm

Computed Head Thickness per EN13445 - 7.5.4:
= max(es,eb,ey) + c + cext
= max(0.2265,0.8128,0.3694) + 0.0000 + 0
= 0.8128 + 0.0000 + 0.0000
= 0.8128 mm

The head is suitable for the design pressure.

Actual stress at design pressure cannot be compute because the thickness for buckling pressure controls.

Computed Maximum Allowable Working Pressure - Design [MAWP]:
MAWP - Phydro = 819.3087 - 4.1632 = 815.1456 kPa

4.6 Hydrostatic Test Pressure Results:

Note: The Hydrotest Pressure Derivation is an Iterative Process
Limited by: Ellipse Head Node: 110 to 120
Hydrotest pressure is based upon stress (ftest) in the weakest element:
Note: 1.5 / 1.05 = 1.429, The PED requirement is 1.43
Test Pressure = Calc Test Press - Liquid Head
= 968.071 - 4.166 = 963.905 kPa

4.7 Stress on Elements due to Test Pressure

Stresses on Elements due to Test Pressure				
From	To	Stress Induced	Allowable Stress	Ratio
10	20	60.6	265	0.229
40	50	60.9	265.0	0.230
50	60	76.2	265.2	0.287
60	70	164.5	265.0	0.621
70	80	148.3	265.0	0.560
100	110	147.9	265.0	0.558
110	120	160.0	160.0	1

Table-1: Stress on Elements due to Test Pressure.

Elements Suitable for Internal Pressure.

4.8 Weight Summary:

Fabricated Wt.- Bare Weight W/O Removable Internals = 1011.3 kgm
Shop Test Wt.- Fabricated Weight + Water (Full)= 6002.4 kgm
Shipping Wt.- Fab. Wt + Rem. Intls.+ Shipping App.=1011.3 kgm
Erected Wt.- Fab. Wt + Rem. Intls.+ Insul. (etc)=1011.3 kgm
Ope. Wt. no Liq - Fab. Wt + Intls. + Details + Wghts.=1011.3 kgm
Operating Wt.- Empty Wt + Operating Liq. Uncorroded = 5747.9 kgm
Field Test Wt. – Empty Weight + Water(full) = 6002.4 kgm
Mass of upper 1/3 of the Vertical Vessel = 3061 kgm

5. CONCLUSIONS

Following the conclusions drawn from the above data and results:

- The vessel designed is safe for internal presure. The elements such as cylindrical shell, conical shell, ellipsoidal head are in safe condition.
- The vessel sustains the hydrotest pressure applied and from Table-1 it can be observed that the stress values induced in the elements are less than the allowable stress.
- The time required for designing and evaluating a pressure vessel is reduced profitably.
- The results obtained can be compared with the analytical results obtained using the EN-13445 Code.

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