Mechanical design of vertical pressure vessel for air receiver using software

Cokorda Prapti Mahandari and Dani Kurniawan

Mechanical Engineering Department, Faculty of Industrial Technology, Gunadarma University, Jakarta-Indonesia
E-mail: coki@staff.gunadarma.ac.id

Abstract

There are many applications of pressure vessels in industry. A vertical pressure vessel as an air receiver had been designed implementing graphical based software. Input parameters for mechanical design of this vessel were provided by one of pressure vessel manufacturer as the following: volume, diameter, design pressure, material type for each element of pressure vessel and corrosion allowance. Analyses were conducted on the component of pressure vessel mainly: head, shell, nozzle, manhole and leg. The result presents thickness of head, thickness of shell, thickness of nozzle for drain and manhole, and axial compression on the leg. Inspection on extreme fiber elongation on head and shell had been also carried out. In addition determination for the requirement of Post Weld Heating Treatment (PWHT) had been also discussed. The results present partially as they were generated except for PWHT checked that presents on table.

Key words: air receiver, pressure vessel, design, PWHT

1. Background

An air receiver is very important for compressed air system to storage the compressed air. The main function of air receiver is to equalize the pressure variation for the start and stop and modulate sequence of the compressor or it can be as a pulsation damper. Compressor should not run continuously and air receiver store and deliver air pressure when the compressor is not running. Moreover by storage the compressed air, it maintains the pressure to be constant from volume variation of the consumption and demand of the system. In addition air receiver can collect condensate and water contained in the air after compressor or can serve as a moisture trap.

Two different kind of air receiver are primary receiver which is located close to the compressor and secondary receiver which is near the system consumers as it is illustrated on Figure 1[1].

Compressed air commonly store in a tank or pressure vessel. Pressure vessels indeed are containers for the storage of compressible fluids. Such vessels can be extremely dangerous if not used properly because of the abundant stored energy created when fluids are compressed. A sudden release of this energy may have catastrophic explosive consequences. In the interest of safety, it is essential that the pressure vessels are manufactured strictly in accordance with a reputable engineering standard or code. Some of the relevant standards for pressure vessels are BS 470; Access and inspection openings for pressure vessels, BS 5169; Fusion-welded steel air receiver, BS 5500; Unfired fusion welded pressure vessels, BS 1101; Specification for pressure container for paint and other substances, ASME Boilers and Pressure Vessel Code – section VIII Division 1 and Division 2, JIS-B8243; Japanese Industrial Standard – Construction of Pressure Vessels, BS 4870; Approval testing of welding procedures, BS 4871; Approval testing of welders working to approved welding procedure; ASME Welding and Brazing Qualifications–Section IX Safety Fittings & Ancillaries, BS 1123; Specifications for safety valves, gauges and other safety fittings for air receivers and compressed air installation, BS 1780; Bourdon tube pressure and vacuum gauges, and BS 2915; Bursting discs and bursting disc assemblies.

There is extreme danger in the use of pressure vessel of unsound or questionable construction. With the hazards involved, pressure vessels must design with great care and full compliance with the applicable codes and legislation. This research discussed about the structural design instead of the fluid or thermodynamic process. The step for designing a pressure vessel involved abundant tedious mathematical calculation. However application of software for this purpose had overcome this problem. One of software for pressure vessels design is PV Elite. This graphical based software has GUI (Graphical User Interface) so that the drawing process can be accomplished easily and the input parameter can be submitted to the same screen. This research utilized PV Elite.
software for designing the structure of vertical pressure vessel for particular air receiver. It is in full compliance with ASME section VIII [3]. Analysis would be run on head, shell, nozzle manhole and leg. Moreover determination of the need for PWHT would also be investigated.

Study on this similar topic has been done on pressure vessel for three phase separator [3]. Nevertheless the pressure vessel was horizontal and analysis was done on elements of pressure vessel including the saddle without PWHT checked.

2. Research Method

Air receiver specification was obtained from the pressure vessel manufacturer. Design parameter would be the input parameters which were as the following: volume of pressure vessel, shell diameter, design pressure, design temperature and maximum corrosion allowance. Design procedure and equations follows ASME Code Section VIII. Since the equations involved will appear on the result of analysis, they are not presented in this section. Analysis was conducted based on flowchart that is shown on Figure 2.

Figure 2. Flowchart of the research method.

Material type for each elements, design pressure, design temperature, shell diameter, and corrosion
allowance had already determined by the industry that ordered the air receiver. These parameters would be submitted to the input screen that showed in the same screen whenever the drawing element was sketch. Analysis was started on each element then on the pressure vessel. The output of analysis can be presented in many features. It can be in the form of table, or export to word processor in the form of final report. Since this research have not completed yet, the output would be presented as they are generated. Even though the result for complete PWHT checked is presented on a table.

3. Result and discussion

Analysis of the pressure vessel element was started with drawing and setting the input parameter on head as it is shown on Figure 3.

![Figure 3. Ellipsoidal bottom head of vessel and input data screen.](image)

The result of analysis is presented partly as they were generated just as the following:

**Thickness Due to Internal Pressure [Tr]:**

\[
( P \times (D+2 \times CA) \times K) / (2 \times S \times E\cdot0.2 \times P) \text{ Appendix 1-4(c)}
\]

\[
= (160.000 \times (54.1730 + 2 \times 0.0625) \times 1.00) / (2 \times 20000.00 \times 1.00-0.2 \times 160.000)
\]

\[
= 0.2174 + 0.0625 = 0.2799 \text{ in}
\]

**Max. All. Working Pressure at Given Thickness [MAWP]:**

\[
(2 \times S \times E \times (T-Ca))/(K \times (D + 2 \times Ca) + 0.2 \times (T-Ca)) \text{ per Appendix 1-4 (c)}
\]

\[
= (2\times20000.00\times1.00\times0.3509)/(1.00\times(54.1730+2\times0.0625)+0.2\times0.3509)
\]

\[
= 258.155 \text{ psig}
\]

**Maximum Allowable Pressure, New and Cold [MAPNC]:**

\[
= (2 \times S \times E \times T)/(K \times D + 0.2 \times T) \text{ per Appendix 1-4 (c)}
\]

\[
= (2 \times 20000.00 \times 1.00 \times 0.4134)/(1.00 \times 54.1730 + 0.2 \times 0.4134)
\]

\[
= 304.769 \text{ psi}
\]

**Actual stress at given pressure and thickness [Sact]:**

\[
= (P \times (K \times (D + 2 \times CA) + 0.2 \times (T-CA)))/(2 \times E \times (T-CA))
\]

\[
= (160.000 \times (1.00 \times (54.1730 + 2 \times 0.0625) + 0.2 \times 0.3509))/(2 \times 1.00 \times
\]

\[
= 12395.634 \text{ psi}.
\]

**Required Thickness of Straight Flange = 0.281 in**

**Percent Elongation per UCS-79**

\[
(75\times\text{nom}/Rf)\times(1-Rf/Ro) = 3.814 \%
\]

**Min Metal Temp. w/o impact per UCS-66**

\[
-17 \text{ F}
\]

**Min Metal Temp. at Rqd thickness**

\[
(UCS \cdot 66.1)\times(\text{rat} \cdot 0.62) = -55 \text{ F}
\]

**Min Metal Temp. w/o imoact per USC-66**

\[
-20 \text{ F}
\]
Analysis on shell was also conducted by drawing and inputting parameters just as it is shown on Figure 4. The results are presented partly in the following:

**Thickness Due to Internal Pressure \([T_r]\):**
\[
T_r = \frac{P \times (D/2 + Ca)}{(S \times E \times 0.6 \times P)} \text{ per UG-27 (c)(1)}
\]
\[
= \frac{160.000 \times 54.1730/2 + 0.0625}{20000.00 \times 1.00 \times 0.6 \times 160.000}
\]
\[
= 0.2182 + 0.0625 = 0.2807 \text{ in}
\]

**Max. All. Working Pressure at Given Thickness \([\text{MAWP}]\):**
\[
\text{MAWP} = \frac{S \times E \times (T-Ca)}{((D/2 + Ca) + 0.6 \times (T-Ca))} \text{ per UG-27 (c)(1)}
\]
\[
= \frac{20000.00 \times 1.00 \times 0.3509}{54.1730/2 + 0.6 \times 0.3509}
\]
\[
= 256.500 \text{ psig}
\]

**Maximum Allowable Pressure, New and Cold \([\text{MAPNC}]\):**
\[
\text{MAPNC} = \frac{S \times E \times T}{(D/2+0.6 \times T)} \text{ per UG-27 (c)(1)}
\]
\[
= \frac{20000.00 \times 1.00 \times 0.4134}{54.1730/2 + 0.6 \times 0.4134}
\]
\[
= 302.464 \text{ psig}
\]

**Actual stress at given pressure and thickness \([\text{Sact}]\):**
\[
\text{Sact} = \frac{P \times ((D/2+Ca)+0.6 \times (T-CA))}{(E \times (T-CA))}
\]
\[
= \frac{160.000 \times 54.1730/2 + 0.0625 + 0.6 \times (0.3509)}{1.00 \times (0.3509)}
\]
\[
= 12475.634 \text{ psi}
\]

**Percent Elongation per:**
\[
\text{UCS-79} \quad (50 \times t_{nom/pt}) x (1-Rf/Ro) = 0.865 \%
\]

**Min Metal Temp. w/o impact per:**
\[
\text{UCS-66} \quad -17 \quad \text{F}
\]

**Min Metal Temp. at Req thickness:**
\[
\text{UCS 66.1}([ \text{rat 0.62}] = -55 \quad \text{F}
\]

**Min Metal Temp. w/o impact per:**
\[
\text{UG-20(f)} = -20 \quad \text{F}
\]

According to the order specification of the air receiver, unit design must be in British System Unit. However changing the unit is very simple because it is provided in the software. Not only the unit system but also the design codes are offered.

There are 8 nozzles on the air receiver and one of nozzle calculation is presented and the input data screen for nozzle drain is shown on Figure 5.
There is a manhole on the shell of air receiver and it is considered as a nozzle. Manhole is necessary for repair work or inspection and clean out the air receiver. Manhole sizing design includes not only outside diameter or dimension but also thickness of its wall and the distance or leg between pipe openings [4]. Input data for analyzing manhole is almost similar to Figure 5 and then the result partially is presented. Complete analysis of nozzles and manhole should discuss other parameters such as area, weld leg, weld size calculation, stress reduction factor, reinforcement thickness, reinforcement area, etc [5, 6, and 7]. These parameters appeared on the generated results however in this paper they are presented partially. Leg or support analysis presented also partially results. It presented axial compression on leg only. Others parameter such as bolting size requirement for leg, torsional buckling stress, bolting size requirement for leg base plate, moment at base plate, base plate lifting moment, base plate require thickness, etc.

PWHT checked for the whole elements of pressure vessel are listed on Table 1. It concluded that this pressure vessel did not need PWHT as all element thicknesses are less than the thickness limit for PWHT. Then the result of total weight calculations is demonstrated. The inclusive pressure vessel for air receiver is presented on Figure 7 and leg analyses are exhibited subsequently.

<table>
<thead>
<tr>
<th>NOZZLE CALCULATION, Description: Drain</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASME Code, Section VIII, Division 1, 2007, UG-37 to UG-45</td>
</tr>
<tr>
<td>Actual Nozzle Inside Diameter Used in Calculation 0.815 in.</td>
</tr>
<tr>
<td>Actual Nozzle Thickness Used in Calculation 0.250 in.</td>
</tr>
<tr>
<td>Nozzle input data check completed without errors.</td>
</tr>
<tr>
<td>Req'd thk per UG-37(a) of Elliptical Head, Tr (Int. Press)</td>
</tr>
<tr>
<td>= (Px(Kx(D+2xCa)))/(2xSxE-0.2xP) per UG-37(a)(3)</td>
</tr>
<tr>
<td>= (160.00x(0.90x(54.1730+2x0.0625)))/(2x20000x1.00-0.2x160.00)</td>
</tr>
<tr>
<td>= 0.1956 in</td>
</tr>
<tr>
<td>Req'd thk per UG-37(a) of Nozzle Wall, Trn (Int. Press)</td>
</tr>
<tr>
<td>= (Px(D/2+CA))/(SxE-0.6xP) per UG-27 (c)(1)</td>
</tr>
<tr>
<td>= (160.00x(0.8150/2+0.0625))/(17100x1.00-0.6x160.00)</td>
</tr>
<tr>
<td>= 0.0044 in</td>
</tr>
<tr>
<td>Nozzle Reqd Thickness (Trn) Max(Setup File, Trn) 0.134 in</td>
</tr>
<tr>
<td>Effective material diameter limit, Di 2.0168 in</td>
</tr>
<tr>
<td>Effective material thickness limit, no pad Trn 0.4888 in</td>
</tr>
</tbody>
</table>
Table 1. *Post Weld Heat Treatment (PWHT)* according to UCS - 56 and UW – 40.

<table>
<thead>
<tr>
<th>Element Descriptions</th>
<th>Material</th>
<th>Nominal thickness</th>
<th>PWHT Thickness limit</th>
<th>Necessary or not necessary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ellipsoidal Head (Top Head)</td>
<td>P No. Group No.</td>
<td>0.4724 Inch</td>
<td>1-1/2 Inch</td>
<td>Not Necessary</td>
</tr>
<tr>
<td>Shell Plate</td>
<td>1 1</td>
<td>0.4724 Inch</td>
<td>1-1/2 Inch</td>
<td>Not Necessary</td>
</tr>
<tr>
<td>Ellipsoidal Head (Bottom Head)</td>
<td>1 1</td>
<td>0.4724 inch</td>
<td>1-1/2 Inch</td>
<td>Not Necessary</td>
</tr>
<tr>
<td>Nozzle Neck N1, N2, N3</td>
<td>1 1</td>
<td>0.344 Inch</td>
<td>1-1/2 Inch</td>
<td>Not Necessary</td>
</tr>
<tr>
<td>Nozzle Neck N4, N5</td>
<td>1 1</td>
<td>0.250 Inch</td>
<td>1-1/2 Inch</td>
<td>Not Necessary</td>
</tr>
<tr>
<td>Nozzle Neck N6</td>
<td>1 1</td>
<td>0.250 Inch</td>
<td>1-1/2 Inch</td>
<td>Not Necessary</td>
</tr>
<tr>
<td>Nozzle Neck N7</td>
<td>1 1</td>
<td>0.4724 Inch</td>
<td>1-1/2 Inch</td>
<td>Not Necessary</td>
</tr>
<tr>
<td>Nozzle Neck N8</td>
<td>1 1</td>
<td>0.250 Inch</td>
<td>1-1/2 Inch</td>
<td>Not Necessary</td>
</tr>
<tr>
<td>Nozzle Neck MH</td>
<td>1 1</td>
<td>0.4724 Inch</td>
<td>1-1/2 Inch</td>
<td>Not Necessary</td>
</tr>
<tr>
<td>Repad for Nozzle MH</td>
<td>1 1</td>
<td>0.4724 Inch</td>
<td>1-1/2 Inch</td>
<td>Not Necessary</td>
</tr>
<tr>
<td>Lifting Lug</td>
<td>1 1</td>
<td>1.000 Inch</td>
<td>1-1/2 Inch</td>
<td>Not Necessary</td>
</tr>
<tr>
<td>Repad for Lifting Lug</td>
<td>1 1</td>
<td>0.4724 inch</td>
<td>1-1/2 Inch</td>
<td>Not Necessary</td>
</tr>
<tr>
<td>Support Leg</td>
<td>1 1</td>
<td>0.591 Inch</td>
<td>1-1/2 Inch</td>
<td>Not Necessary</td>
</tr>
<tr>
<td>Repad for Support Leg</td>
<td>1 1</td>
<td>0.4724 inch</td>
<td>1-1/2 Inch</td>
<td>Not Necessary</td>
</tr>
</tbody>
</table>

---

NOZZLE CALCULATION. Description: Manhole
ASME Code, Section VIII, Division 1, 2007, UG-37 to UG-45

Actual Nozzle Inside Diameter Used in Calculation 18.814 in.
Actual Nozzle Thickness Used in Calculation 0.593 in.

Nozzle input data check completed without errors.

Reqd thk per UG-37(a) of Cylindrical Shell, Tr [Int. Press]
= (Px(D/2+CA))/((SxE-0.6xP) per UG-27 (c)(1)
= (160.00x(54.1730/2+0.0625))/(20000x1.00-0.6x160.00)
= 0.2182 in

Reqd thk per UG-37(a) of Nozzle Wall, Trn [Int. Press]
= (Px(D/2+CA))/((SxE-0.6xP) per UG-27 (c)(1)
= (160.00x(18.8140/2+0.0625))/(17100x1.00-0.6x160.00)
= 0.0891 in

Nozzle Reqd Thickness (Trn) Max (Setup File, Trn) 0.134 in

UG-40, Thickness and Diameter Limit Results: [Int. Press]
Effective material diameter limit, DI 37.8780 in
Effective material thickness limit, no pad Tlnp 0.8772 in
Effective material thickness limit, pad side Tlwp 0.8772 in

---

Element and Detail Weights

<table>
<thead>
<tr>
<th>From</th>
<th>To</th>
<th>Total Ele</th>
<th>Total Ele</th>
<th>Total Ele</th>
<th>Total Dt</th>
<th>Oper. Wgt</th>
<th>Empty Wgt</th>
<th>Oper. Wgt</th>
<th>Hydro. Wgt</th>
<th>Offset Mom</th>
<th>No Liquid</th>
<th>Oper. Wgt</th>
<th>Hydro. Wgt</th>
<th>Offset Mom</th>
<th>No Liquid</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>Legs</td>
<td>2321.20</td>
<td>2321.20</td>
<td>5993.06</td>
<td>0.00000</td>
<td>2321.20</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Legs</td>
<td>20</td>
<td>-1740.90</td>
<td>-1740.90</td>
<td>-4494.80</td>
<td>0.00000</td>
<td>-1740.90</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>30</td>
<td>3778.23</td>
<td>3778.23</td>
<td>13766.2</td>
<td>27351.8</td>
<td>3778.23</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>40</td>
<td>586.720</td>
<td>586.720</td>
<td>1504.68</td>
<td>0.00000</td>
<td>586.720</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Cumulative Vessel Weight

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>Legs</td>
<td>2321.20</td>
<td>2321.20</td>
<td>5993.06</td>
<td>0.00000</td>
<td>2321.20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Legs</td>
<td>20</td>
<td>-1740.90</td>
<td>-1740.90</td>
<td>-4494.80</td>
<td>0.00000</td>
<td>-1740.90</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>30</td>
<td>3778.23</td>
<td>3778.23</td>
<td>13766.2</td>
<td>27351.8</td>
<td>3778.23</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>40</td>
<td>586.720</td>
<td>586.720</td>
<td>1504.68</td>
<td>0.00000</td>
<td>586.720</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
RESULTS FOR LEGS: HydroTest Case Description: LEGS
Legs attached to: bottom head
Section Properties: Single Angle L6X6X0.6250
USA AISC 1989 Steel Table

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leg Length from Attachment to Base</td>
<td>58.189 in</td>
</tr>
<tr>
<td>Distance Leg Up Side of Vessel</td>
<td>8.000 in</td>
</tr>
<tr>
<td>Number of Legs</td>
<td>4</td>
</tr>
<tr>
<td>Cross Sectional Area for L6X6X0.6250</td>
<td>7.110 in²</td>
</tr>
<tr>
<td>Section Inertia (strong axis)</td>
<td>24.200 in^4</td>
</tr>
<tr>
<td>Section Inertia (weak axis)</td>
<td>24.200 in^4</td>
</tr>
<tr>
<td>Section Modulus (strong axis)</td>
<td>5.660 in³</td>
</tr>
<tr>
<td>Section Modulus (weak axis)</td>
<td>5.660 in³</td>
</tr>
<tr>
<td>Radius of Gyration (strong axis)</td>
<td>1.840 in</td>
</tr>
<tr>
<td>Radius of Gyration (weak axis)</td>
<td>1.840 in</td>
</tr>
<tr>
<td>Leg Orientation - Strong Axis</td>
<td></td>
</tr>
<tr>
<td>Overturning Moment at top of Legs</td>
<td>8529.5 in-lb</td>
</tr>
<tr>
<td>Total Weight Load at top of Legs</td>
<td>17228.2 lbf</td>
</tr>
<tr>
<td>Total Shear force at top of Legs</td>
<td>157.0 lbf</td>
</tr>
<tr>
<td>Additional force in Leg due to Bracing</td>
<td>0.0 lbf</td>
</tr>
<tr>
<td>Occasional Load Factor</td>
<td>1.333</td>
</tr>
<tr>
<td>Effective Leg End Condition Factor k</td>
<td>1.000</td>
</tr>
</tbody>
</table>

Note: The Legs are Not Cross Braced

The Leg Shear Force includes Wind and Seismic Effects

Maximum Shear at top of one Leg [Vleg]:

\[ V_{\text{max}}(\text{Wind, Seismic} + F_{\text{add}}) / (I_{\text{max}} / I_{\text{tot}}) \]

\[ V_{\text{max}} = (157.0 + 0.0) / (24.1 / 96.29) \]

\[ V_{\text{max}} = 39.24 \text{ lbf} \]

Axial Compression, Leg furthest from N.A. [Sma]

\[ S_{\text{max}} = ((W/N_{\text{leg}}) + (M_{\text{leg}}/(N_{\text{leg}} + R_{\text{n}}))) / A_{\text{leg}} \]

\[ S_{\text{max}} = (17228 / 4) + (102353 / (2 \times 31.75)) / 7.110 \]

\[ S_{\text{max}} = 624.66 \text{ psi} \]

Axial Compression, Leg closest to N.A. [Sva]

\[ S_{\text{sva}} = (W / N_{\text{leg}}) / A_{\text{leg}} \]

\[ S_{\text{sva}} = (17228 / 4) / 7.110 \]

\[ S_{\text{sva}} = 605.77 \text{ psi} \]
4. Conclusion
Mechanical design of a vertical pressure vessel for air receiver has been accomplished incorporating graphical-based software. Analysis has been carried out on the elements of pressure vessel and the result can be presented rapidly.

Further research need to explore environmental parameter such as earthquake, thermal load, fluctuation load and so on. Moreover dynamic processes in design need to employ for optimization instead of fixing the input parameter.

References