Failure Analysis of A Thin-walled CNG Cylindrical Pressure Vessel

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Abstract: The purpose of this paper is to analyse the failure of a thin–walled pressure vessel subjected to internal pressure. The cylinder with thin–walled is assumed it is generally used as pressure vessel with open end or closed end. The compressed natural gas (CNG)cylinder pressure vessel become important in (natural gas vehicle )NGV fuel driving system because demand in CNG base as increase. CNG pressure has four types made with fully metal, hoop wrapped with metal liner, fully wrapped with metal liner or composite. This paper discusses the case failure analysis in type I (CNG1). The CNG1 vessel constructed with AISI 4130 Low alloy steel. The vessel capacity is 50 litter and diameter 229mm and length is 1525mm. operating pressure is internal pressure (20MPa). The thickness of structure at various part of vessel is calculated by using design equation. Based on Hill’s criterion and Von-Mises criterion, the operating and failure pressure of the vessel are predicted. In this paper focus on, to apply thin –walled (CNG1) vessel with failure theory and to prevent stress related vessel rupture and catastrophic failure. Finite element analysis of hemispherical head and cylindrical shell position is done by using COMSOL Multiphysics.

Keywords: (CNG1) Pressure Vessel, Design Thickness And Stress, Numerical Simulation, Failure Analysis, COMSOL Multiphasic.

I. INTRODUCTION

Pressure vessels are used in a number of industries; for example, the power generation industry for fossil and nuclear power, the petrochemical industry for storing petroleum oil as well as storing gasoline in service stations, and compressed natural gas (CNG) cylinder pressure vessel. Generally speaking, pressurized equipment is required for a wide range of industrial plant for storage and manufacturing purposes. The size and geometric form of pressure vessels vary greatly from the large cylindrical vessels used for high-pressure gas storage to the small size used as hydraulic units for aircraft and automobile. Both CNG and hydrogen are stored on board in cylindrical pressure vessels. In practice, CNG pressure vessel is classified as thin wall cylinder. So, the wall thickness, t is small in comparison with the circumferential radius of curvature, r. If the ratio r/t > 10, the cylinder is consider to be thin shell.

Further ,most shell used in vessel construction are thin (membrane)shell in the range 10r ≤ R ≤ 500r, whose important characteristic is that bending stress due to external loads are of high intensity only in close proximity to the area where the load are applied. Approximate solutions of the shell theory can be applied to pressure vessels with more complex shells. There are four types of pressure vessels used in the storage of fuel gas on automobiles.

- CNG1 cylinder - All metal.
- CNG2 cylinder - Hoop Wrapped Composite.
- CNG3 cylinder-Fully Wrapped Composite with Metal Liners.
- CNG4 cylinder-Fully Wrapped Composite with Non-Metallic Liners

Types of pressure vessel are shown in figure 1.

II. BACKGROUND OF DESIGN

CNG pressure vessels normally consist of four components as shown in figure 5 based on standards has been follow. These methods must be strictly in accordance with
the provisions of the prevailing code. The methods described here are in line with the requirements of ASME Section VIII Div (1) and hence shall meet almost all the requirements of other codes for pressure vessel manufacture.


This paper presents solutions for a cylindrical vessel with hemispherical head and ellipsoidal bottom. Final mathematical expressions for calculating design thickness for each part. By using those expressions, and by connecting membrane stress theory, a method for determining strength of pressure vessels with hemispherical heads and ellipsoidal bottom, which is suitable for designing, was developed. A special computer programmer was created for the application of this method. Computer calculation was done on a selected numerical example, and the analysis results were shown in a diagram.

A. Specification Data of CNG1 Pressure Vessel

Table I: Design Parameter of CNG1 Pressure Vessel

<table>
<thead>
<tr>
<th>S.NO</th>
<th>Design parameter</th>
<th>symbol</th>
<th>value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Vessel dimension</td>
<td>D_v</td>
<td>229</td>
<td>mm</td>
</tr>
<tr>
<td></td>
<td>length</td>
<td>L_v</td>
<td>1525</td>
<td>mm</td>
</tr>
<tr>
<td>2</td>
<td>Load</td>
<td>P_1</td>
<td>20</td>
<td>MPa</td>
</tr>
<tr>
<td>4</td>
<td>Material Low alloy steel (Al 4130)</td>
<td>E</td>
<td>20500</td>
<td>N/mm²</td>
</tr>
<tr>
<td></td>
<td>Elastic modulus</td>
<td>E</td>
<td>20500</td>
<td>N/mm²</td>
</tr>
<tr>
<td></td>
<td>Poisson’s ratio</td>
<td>ν</td>
<td>0.285</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Yield strength</td>
<td>σ_y</td>
<td>460</td>
<td>MPa</td>
</tr>
<tr>
<td></td>
<td>Mass density</td>
<td>ρ</td>
<td>7850</td>
<td>Kg/m³</td>
</tr>
</tbody>
</table>

B. Design Formula of CNG Pressure Vessel parts

Table II: Resume of Pressure Vessel Formula-ASME Section I & ASME Section VIII

<table>
<thead>
<tr>
<th>Item</th>
<th>Thickness (mm)</th>
<th>Pressure, P(MPa)</th>
<th>Stress, σ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylindrical shell</td>
<td>t = \frac{P_R}{(R - 0.6t)}</td>
<td>\frac{P}{(R - 0.6t)} \sigma = \frac{P(R + 0.6t)}{t}</td>
<td></td>
</tr>
<tr>
<td></td>
<td>t = \frac{P_R}{(2R + 0.6t)}</td>
<td>\frac{P}{(2R + 0.6t)} \sigma = \frac{P(R - 0.4t)}{t}</td>
<td></td>
</tr>
<tr>
<td>Hemispherical head</td>
<td>t = \frac{P_R}{(2R - 0.2t)}</td>
<td>\frac{P}{(2R - 0.2t)} \sigma = \frac{P(R + 0.2t)}{2t}</td>
<td></td>
</tr>
<tr>
<td>Ellipsoidal head</td>
<td>t = \frac{P DK}{(2R - 0.2t)}</td>
<td>\frac{P}{(2R - 0.2t)} \sigma = \frac{P(DK + 0.2t)}{2t}</td>
<td></td>
</tr>
</tbody>
</table>

III. Membrane Stress Analysis of Pressure Vessel

Stresses in the walls of pressure vessels occur due to different types of loads, depending on the purpose of the vessel and on different influences that a vessel is subjected to during exploitation. Internal pressure has the biggest influence on the amount of stress, so all other types of loads are considered to be less important. Solutions of the shell theory equation show that internal pressure which occurs in the walls of the vessel can be, under certain conditions, determined by principal stress theory, Von-Mises theory and stress intensity (Trsca’s theory).

1. First principal stress theory

For cylindrical shell

\[ \sigma_1 = \frac{P(R + 0.6t)}{t} \]

2. Second principal stress theory

For hemispherical head

\[ \sigma_1 = \frac{P(R + 0.2t)}{2t} \]

3. Third principal stress theory

For cylindrical shell

\[ \sigma_2 = \frac{P(R + 0.6t)}{t} \]

4. Von-Mises stress theory

\[ Y^2 = \sigma_1^2 - \sigma_1\sigma_2 + \sigma_2^2 \]

5. Stress intensity theory

\[ Y = \sigma_1 - \sigma_3 \]

6. First principal strain

\[ \varepsilon_1 = \frac{1}{E} (\sigma_1 - \nu \sigma_2) \]

7. Second principal strain

\[ \varepsilon_2 = \frac{1}{E} (\sigma_2 - \nu \sigma_1) \]

8. Third principal strain

\[ \varepsilon_3 = \frac{1}{E} (\sigma_1 + \sigma_2) \]

9. Equivalent strain theory

\[ \varepsilon = \left[ \frac{2}{3} (\varepsilon_1^2 + \varepsilon_2^2 + \varepsilon_3^2) \right]^{1/2} \]

IV. Calculation Results of CNG1 Pressure Vessel

Table III: Result Table of Thickness for Pressure Vessel Parts

<table>
<thead>
<tr>
<th>parts</th>
<th>Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylindrical shell</td>
<td>5.8</td>
</tr>
<tr>
<td>Hemispherical head</td>
<td>8.7</td>
</tr>
<tr>
<td>Ellipsoidal bottom</td>
<td>11.4</td>
</tr>
<tr>
<td>Nozzle</td>
<td>4</td>
</tr>
</tbody>
</table>
TABLE IV: RESULT TABLE OF STRESSES FOR PRESSURE VESSEL PARTS

<table>
<thead>
<tr>
<th>Stress</th>
<th>Shell</th>
<th>Head</th>
<th>Bottom</th>
<th>Nozzle</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st principal stress, $\sigma_1$ (MPa)</td>
<td>388.2</td>
<td>124.1</td>
<td>109.4</td>
<td>50</td>
</tr>
<tr>
<td>2nd principal stress, $\sigma_2$ (MPa)</td>
<td>184.1</td>
<td>124.1</td>
<td>109.4</td>
<td>15</td>
</tr>
<tr>
<td>Von-Mises stress, Y (MPa)</td>
<td>336.3</td>
<td>124.1</td>
<td>109.4</td>
<td>44.4</td>
</tr>
<tr>
<td>Stress intensity (MPa)</td>
<td>0.0016</td>
<td>0.00043</td>
<td>0.0003</td>
<td>0.00022</td>
</tr>
<tr>
<td>1st principal strain, $\varepsilon_1$</td>
<td>0.0003</td>
<td>0.00043</td>
<td>0.0003</td>
<td>0.00003</td>
</tr>
<tr>
<td>2nd principal strain, $\varepsilon_2$</td>
<td>-0.008</td>
<td>-0.0003</td>
<td>-0.0003</td>
<td>-0.00009</td>
</tr>
<tr>
<td>Equivalent strain</td>
<td>0.0015</td>
<td>0.00057</td>
<td>0.0005</td>
<td>0.00019</td>
</tr>
</tbody>
</table>

V. NUMERICAL ANALYSIS OF PRESSURE VESSEL

To analysis the Von-Mises stress, COMSOL software has been used. The pressure vessel for the analysis is used natural gas with internal pressure 24MPa. The material is low alloy steel AISI 4130. Figure 3 show stresses distributed in CNG1 pressure vessel with internal pressure 24MPa.

VI. RESULTS AND DISCUSSIONS

The failure pressure of shell portion is predicted by using finite element analysis software. The failure of the structure starts from the pressure of 24 MPa and the complete failure of the structure occur at 28MPa. The operating pressure of the structure should not exceed 20MPa. These results are shown in table 5 and figure 5, and 6.

TABLE V: OPERATING AND FAILURE PRESSURE OF THIN-WALLED VESSEL STRUCTURE

<table>
<thead>
<tr>
<th>Pressure vessel</th>
<th>Operating pressure</th>
<th>Failure pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylindrical</td>
<td>20MPa</td>
<td>Failure starts from 24MPa, complete occurs at 28MPa</td>
</tr>
</tbody>
</table>

An approximative analytical solution can be obtained for the cylindrical pressure vessel with COMSOL Multiphysics. Following Hill’s criterion, the yield will occur for

$$P^2 [F\left(\frac{R_0}{T_0} + 1\right)^2 + G(1 + \frac{R_0}{2T_0})^2 + H\left(\frac{R_0}{2T_0} - \frac{R_0}{T_0}\right)^2] = 1$$ (12)

Using the model constants, $F = G = 2.47 \times 10^{-13}/P_0^2$ and $H = 4.42 \times 10^{-14}/P_0^2$ the analytical onset of yielding occurs for $p=24.2$MPa as compared to $P=24$ MPa which is the result calculated by COMSOL. Figure 11 shows the Von-Mises stress contours at the onset of yielding. For low alloy steel with yield stress at 460 MPa, the yield stress is reached for $P=28$ MPa.

Figure 3. Von-Mises stress distribution of pressure vessel.

Figure 4. Von-Mises stress distribution of pressure vessel

Figure 5. Von-Mises stress distribution of pressure vessel (pressure 28MPa).
Figure 6. Volume having reached yield stress at various pressures.

Figure 7. Surface Von-Mises stress (Gauss - point evaluation) (Pressure 28MPa)

Figure 8. Surface: Effective plastic strain (Gauss - point evaluation) (Pressure 28MPa)

Surface Von-Mises stress (Gauss - point evaluation) and Surface: Effective plastic strains (Gauss - point evaluation) are shown in figure 7 and 8. Mesh shapes are shown in figure 9 and 10.

VII. CONCLUSION AND RECOMMENDATIONS

From this simple analysis, it can be concluded that this vessel can fail at the internal pressure at 28MPa. Failure occurs when the maximum stress in the part exceeds the yield strength. In this paper the maximum stress exceeds the yield strength at internal pressure 24MPa. It can be seen in figure 6. Therefore failure of the structure starts from the pressure of 24 MPa and the complete failure of the structure occur at 28MPa. In this paper discussed failure analysis for CNG1 pressure vessel with COMSOL Multiphysics. These results are approximated to design limits. Nowadays, CNG1 to CNG4 is used in many automobiles in many countries. Various scenarios of development and manufacture CNG pressure vessels have been discussed and it seems all the CNG pressure vessels (CNG-1 to CNG-4) had their own advantages and disadvantages. The cost of manufactured and material will increased from type-1 to type-4. New solution, manufacturing process or material should be used to reduce the cost but must follow the international standard characteristics. Not only the cost but reliability and life span of tank also must be considered to developed economical and reliable tanks. In the future works, the simulation works to estimate the failure analysis of various type CNG pressure vessels by using COMOL Multiphysics or ANSYS software.
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NOMENCLATURE
\( t \) = thickness (mm)
\( R_i \) = internal radius (mm)
\( P_i \) = internal pressure (MPa)
\( \sigma_y \) = yield strength (MPa)
\( \sigma_1 \) = First principal stress (MPa)
\( \sigma_2 \) = Second principal stress (MPa)
\( \sigma_3 \) = Third principal stress (MPa)
\( \epsilon_1 \) = First principal strain
\( \epsilon_2 \) = Second principal strain
\( \epsilon_3 \) = Third principal strain
\( \epsilon_e \) = equivalent strain
\( \nu \) = poisson’s ratio
\( E \) = Elastic modulus (N/m²)
\( \rho \) = mass density (kg/m³)

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[11] Pavo Baličević1, * - Dražan Kozak2 - Tomislav Mrčela3, Strength of Pressure Vessels with Ellipsoidal Heads”, 1 Josip Juraj Strossmayer University of Osijek, Faculty of Agriculture, Croatia, 2 Josip Juraj Strossmayer University of Osijek, Mechanical Engineering Faculty in Slavonski Brod, Croatia, 3 Josip Juraj Strossmayer University of Osijek, Faculty of Electrical Engineering, Croatia.