Household LPG Cylinder: Effects of different heads and Impact analysis using ANSYS

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Abstract. The aim of this paper is to study the behaviour of a gas-filled LPG (liquefied petroleum gas) cylinder having dissimilar heads (hemispherical, semi-ellipsoidal and torispherical) and its responses subjected to vertical (at the top) and horizontal (side) normal impacts by a solid spherical steel ball of mass 4 kg at different velocities 5, 25 and 50 m/sec using ANSYS. The technical specifications of the gas cylinder necessary for its design calculations are referred from Hindustan Petroleum Corporation Limited (HPCL). The conventional steel is considered as the material for both the cylinder and the impacting ball under the critical gas pressure of 2.5 MPa as per Indian standard, IS 6240. Effects of the critical gas pressure on the cylinders are studied based on the thickness as well as the strength for above heads. The simulated results of ANSYS have good agreement with the theoretical results.

Keywords: LPG cylinder, pressure vessel and Impact analysis.

1. Introduction

It is necessary to modernize the design process of a household LPG (liquefied petroleum gas) cylinder with suitable safety provisions for minimizing the incidents which cause lots of casualties every year and damage the cherished infrastructure. The gas leakage, incorrect installation and poor maintenance of the gas cylinder are the primary causes of those incidents. During transportation and handling processes, hardly any safety protocols are followed. The poor maintenance of the cylinder loosen the valve leading to the gas leakage which results unfortunate accidents. The knowledge of the behaviour of a gas-filled cylinder subjected to impact loading is also required for its improved design. The LPG cylinder may be considered as a pressure vessel. Kaptan and Kisioglu [1] presented the fracture analysis of the LPG tanks. Choi et al. [2] estimated design pressure in a prismatic storage vessel of liquefied natural gas. Pendbhaje et al. [3] presented the design and analysis of a pressure vessel. The distribution of stresses on a pressure vessel is obtained by Szekessy [4]. Kumar et al. [5] presented the design analysis of a pressure vessel at different end connections. Mair et al. [6] have used composite materials for gas cylinder for assessment of safety improvements as well as cost and weight savings. Li et al. [7] carried out gas explosion simulations to evaluate the explosion overpressure mitigating effect of safety gap on a cylindrical floating liquefied natural gas vessel. Failure analysis of an exploded CO₂ gas cylinder is done by Pal et al. [8]. Tschirschwitz et al. [9] presented the consequences in case of failure of mobile gas cylinders in fire. Rodrigus and Liburdy [10] given the transient heat transfer model and verification for gas cylinder expansion. The impact problems of a pressure vessel are analyzed by Ren et al. [11], Liao and Jia [12], Choi [13], Hereil et al. [14], Garcia
et al. [15] and, Han and Chang [16] at different velocities of projectiles. This paper is extension of the authors’ [17] earlier work regarding design and analysis of a lightweight LPG cylinder. In this paper, the responses of the filled LPG cylinder of dissimilar heads (hemispherical, semi-elliptical and torispherical) are reported at its critical gas pressure, 2.5 MPa and a numerical simulation for vertical (at the top) and horizontal (side) normal impact on the cylinder by a solid spherical steel ball of mass 4 kg is presented at three different velocities 5, 25 and 50 m/sec.

2. Materials and Technical Specifications
The material for the household LPG cylinder is conventional steel as per the Indian standard, IS 6240. The conventional steel is composed of C: 0.2, Si: 0.25, Mn: 0.90, P: 0.035, S: 0.035 and Al: 0.02 by mole fraction. A solid spherical ball having mass 4 kg and radius 49.66 mm of same material is used as the impactor for the impact analysis. For conventional steel, density 7850 kg/m$^3$, Poisson ratio 0.3, elastic modulus 209 MPa, yield strength 240 MPa and tensile strength 450 MPa are used in the present investigation. The cylinder is designed for the critical gas pressure of 2.5 MPa. The joint efficiency (E) is taken as 1 and the factor of safety is considered as 2.84. The technical specifications of the cylinder necessary for its design calculations are referred from Hindustan Petroleum Corporation Limited (HPCL).

3. Results and Discussion
The dimensioning and meshing of a 2:1 semi-ellipsoidal head cylinder is shown in figure 1. The stress analysis is carried out by two methods; based on thickness and based on strength as indicated in table 1. The distribution of stresses generated due to critical gas pressure, 2.5 MPa, is shown on the LPG cylinder. Thereafter, an Impact Analysis is done in subsequent section. The ASME Boiler Pressure Code, Section-VIII [18] is followed for dimensioning and calculating stresses in the cylinder.

![Figure 1](a) Geometrical modelling (a) Dimensioning in mm and (b) Meshing for semi-ellipsoidal head (2:1) cylinder.
Table 1: Formulae used in theoretical calculation of stresses in the LPG cylinder [18]

| Part                          | Based on Thickness                                      | Based on Stress                                      |
|-------------------------------|---------------------------------------------------------|------------------------------------------------------|
| Cylindrical Shell:            |                                                         |                                                      |
| Longitudinal                  | $\frac{PR_i}{2SE + 0.4P}$                               | $\frac{P(R_i - 0.4t)}{2Et}$                          |
| Circumferential               | $\frac{PR_i}{SE - 0.6P}$                                | $\frac{P(R_i + 0.6t)}{Et}$                          |
| Head:                         |                                                         |                                                      |
| Hemispherical Head            | $\frac{PR_i}{2SE - 0.2P}$                               | $\frac{P(R_i + 0.2t)}{2Et}$                          |
| 2:1 Semi Ellipsoidal Head     | $\frac{PD_i}{2SE - 0.2P}$                               | $\frac{PR_i^2}{2th}$                                |
| Tori-Spherical Head           | $\frac{0.885PL_i}{SE - 0.1P}$                           | $\frac{P(0.5MR_i/t + 0.1)}{E}$                      |

Where, $P$ – design pressure, $S$ – allowable stress, $E$ – joint efficiency, $D_i$ – inner diameter, $R_i$ – inner radius, $L$ – crown radius, $h$ – head height, $r$ – knuckle radius $t$ – thickness and $M$ – coefficient $= 0.25 \left( 3 + \frac{E}{r} \right)$.

3.1. Based on Thickness

In this case, the stresses in the cylinder are determined based on same thickness (2.5 mm). The theoretical stresses are calculated separately for cylindrical shell and heads using the formula given in table 1. The theoretical values of longitudinal and circumferential stresses in cylindrical shell are 78.17 MPa and 158.7 MPa respectively for all heads. The theoretical longitudinal/circumferential stresses in hemispherical, semi-ellipsoidal and tori-spherical heads are 78.85 MPa, 157.20 MPa and 278.49 MPa respectively. The ANSYS simulation of the problem is shown in figure 2. Boundary conditions; cylinder is free from all direction and the internal pressure, 2.5 MPa, are applied. There are 36201, 20003 and 52547 tetrahedral elements and 72441, 40041 and 105127 nodes for hemispherical, semi-elliptical (2:1) and tori-spherical head cylinders respectively. From the ANSYS simulation, it is found that the longitudinal stresses at the centres of cylindrical shells of hemispherical, semi-ellipsoidal and tori-spherical head cylinders are 78.09 MPa, 78.04 MPa and 77.96 MPa respectively whereas, the circumferential stresses are respectively 155.49 MPa, 155.70 MPa and 155.85 MPa. The longitudinal stresses in hemispherical, semi-ellipsoidal and tori-spherical heads are 100.56 MPa, 167.59 MPa and 490.73 MPa respectively whereas, the circumferential stresses are respectively 116.57 MPa, 196.10 MPa and 367.45 MPa. There is minimal differences in masses of hemispherical (10.48 kg), semi-ellipsoidal (10.74 kg) and tori-spherical (10.81 kg) head cylinders. The von-Mises stresses on hemispherical head cylinder are found lesser as compared to semi-elliptical and tori-spherical head cylinders (figure 3). The maximum value (791.99 MPa) of the von-Mises stress generated on tori-
spherical head cylinder (figure 3e) is reasonably more than the tensile strength (450 MPa) of its material, the conventional steel, indicating that tori-spherical head cylinder of thickness 2.5 mm is not safe for storing gas at a critical pressure of 2.5 MPa. It is observed that the theoretical and ANSYS results are quite close at the centre of the cylindrical shell and maximum near the joint end.

![Figure 2](image)

**Figure 2:** Circumferential (a,b,c) and longitudinal (d,e,f) stress distributions on semi-ellipsoidal, hemispherical and tori-spherical head cylinders respectively based on same thickness.

### 3.2. Based on Strength

In this case, thicknesses of different head cylinders are calculated based on their strengths. The theoretical values of longitudinal stresses in cylindrical shells of hemispherical, semi-ellipsoidal and tori-spherical head cylinders are 78.17 MPa, 78.17 MPa and 43.17 MPa respectively whereas, the circumferential stresses are respectively 158.70 MPa, 158.70 MPa and 88.83 MPa. The theoretical
longitudinal/circumferential stresses in hemispherical, semi-ellipsoidal and tori-spherical heads are 78.85 MPa, 157.20 MPa and 154.83 MPa respectively. The ANSYS simulation of the problem is shown in figure 3. There are 36201, 20003 and 51486 tetrahedral elements and 72441, 40041 and 105127 nodes for hemispherical, semi-elliptical and tori-spherical head cylinders respectively. Boundary conditions; cylinder is free from all directions and the internal pressure, 2.5 MPa, are applied. From the ANSYS simulation, it is found that the longitudinal stresses at the centres of cylindrical shells of hemispherical, semi-ellipsoidal and tori-spherical head cylinders are 78.09 MPa, 78.04 MPa and 43.15 MPa respectively whereas, the circumferential stresses are respectively 155.49 MPa, 155.70 MPa and 85.69 MPa. The longitudinal stresses in hemispherical, semi-ellipsoidal and tori-spherical heads are 100.56 MPa, 167.59 MPa and 243.08 MPa respectively whereas, the circumferential stresses are respectively 116.57 MPa, 196.10 MPa and 180.26 MPa. It is observed that when the different head cylinder is designed based on their strength, the thickness for the tori-spherical head cylinder is 4.5 mm whereas its mass is 19.66 kg which is more than the remaining two dissimilar cylinders. Thicknesses and masses of the other two cylinders are same as calculated based on thickness. The von-Mises stresses on hemispherical head cylinder are lower than that of other cylinders. In this case, all the cylinders are safe to store the gas at critical pressure of 2.5 MPa as maximum von-Mises stresses generated on them are below the tensile strength (450 MPa) of their material (steel). The circumferential and longitudinal stress distribution on tori-spherical head cylinder based on strength are shown in figures 3 (a) and 3(b) respectively whereas for other two cylinders, those stresses have similar distributions as based on thickness. For the cases, based on thickness and strength, the von-Mises stresses (figures 3c and 3d) of hemispherical and semi-ellipsoidal head cylinders are same but for tori-spherical head cylinder the von-Mises stresses (figures 3e and 3f) are different. It is also observed that the theoretical and ANSYS results are quite close at the centre of the cylindrical shell and maximum near the joint end.
3.3. Impact Analysis

An impact analysis on the household LPG cylinder for its three different heads (semi-ellipsoidal, hemispherical and tori-spherical) is done subjected to vertical (at the top) and horizontal (side) normal impact at the centre by a solid spherical steel impactor of mass 4 kg using ANSYS software. The impactor strikes the cylinder having critical gas pressure, 2.5 MPa at three different velocities of 5, 25 and 50 m/s and the distributions of stress-strain values on the cylinder are determined. For simulation in ANSYS, the initial condition is, velocity given to the impactor. The boundary conditions are, for vertical impact, the cylinder is fixed from bottom whereas for horizontal impact, cylinder is free to move. The numbers of tetrahedral elements for hemispherical, semi-ellipsoidal and tori-spherical head cylinders are 10362, 11770 and 12114 while the numbers of nodes are 3373, 3818 and 3943 respectively. The meshing for vertical and horizontal normal impacts are shown in figure 4.

The maximum stress-strain values generated on the gas cylinder during the impact are presented in table 2 at different velocities in vertical and horizontal directions. The distributions of equivalent stresses and strains (von-Mises) are shown in figure 5 and figure 6 respectively at the impact velocity of 25 m/s for different heads. It is observed that the stress-strain values on the cylinder increase with the increasing velocity of the impacting ball. The values of stress-strain are found more in the vertical impact as compared to the horizontal impact. The semi-ellipsoidal head cylinder shows more stresses.
in all directions while more strains are found in the hemispherical head cylinder in vertical impact only.

**Table 2:** Maximum stress/strain values for semi-ellipsoidal, hemispherical and tori-spherical head cylinders during impact.

| Velocity (m/s) | Max. Stress (MPa)/ Strain (mm/mm) | Semi-Ellipsoidal Head | Hemispherical Head | Tori-Spherical Head |
|---------------|----------------------------------|------------------------|-------------------|---------------------|
|               | Vertical Impact | Horizontal Impact | Vertical Impact | Horizontal Impact | Vertical Impact | Horizontal Impact |
| 5             | Stress 509.21    | 339.23                | 471.02            | 260.01             | 299.81          | 258.69            |
|               | Strain 0.00453   | 0.00329               | 0.00741           | 0.00256            | 0.00434         | 0.00347           |
| 25            | Stress 2655      | 1231.40               | 2612.80           | 1013               | 1470.40         | 1146.10           |
|               | Strain 0.02162   | 0.01685               | 0.03894           | 0.01274            | 0.01736         | 0.01557           |
| 50            | Stress 5745      | 2442.60               | 4176.3            | 2070               | 2731            | 2150.8            |
|               | Strain 0.04756   | 0.03458               | 0.05766           | 0.02748            | 0.03216         | 0.029747          |
Figure 5: Equivalent (von-Mises) stress distribution on semi-ellipsoidal, hemispherical and torispherical head cylinders respectively after impact for vertical drop (a, b, c) and horizontal side impact (d, e, f) at velocity 25 m/sec.
4. Conclusions
The present investigation reveals that;

- Hemispherical, semi-ellipsoidal (2:1) and tori-spherical head cylinders have the thickness 2.5 mm, 2.5 mm and 4.5 mm respectively at critical pressure of 2.5 MPa for their safe design on the basis of strength.
- Tori-spherical head cylinder is not safe for storing gas at a critical pressure of 2.5 MPa when same thickness is considered as the design criteria.
- The head part of hemispherical head cylinder and the cylindrical part of tori-spherical head cylinder have low stresses whereas the more stresses are found in head part of semi-ellipsoidal head cylinder when the criteria is ‘based on strength’.
- The deformation of LPG cylinder is more during vertical impact (at the top) compared to the horizontal (side) impact.
- The vertical impact on the semi-ellipsoidal head cylinder is more dangerous than that on hemispherical and tori-spherical head cylinders.

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