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Design of liquid oxygen storage tank with welded joints & its Safety

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ABSTRACT: *In this paper we design a high pressure liquid oxygen storage tank. Liquid oxygen storage tank is leak proof container design to hold and store liquid oxygen at cryogenic temperature at a pressure substantially different from the ambient pressure. Design is carried out according to American Society of Mechanical Engineers (ASME) code, deals with the study of various metals. Various methods of fabrication like welding and testing are also included. Using CATIA software 3D model has been prepared. The final Liquid oxygen storage tank has to be designed in a tradeoff between strength and thermal aspects. To overcome the problems in existing storage tank design, in our proposed design the stresses developed and corrosion in the circular cross section with hemispherical end caps welded are very less when compared to flat cap on the storage tank top. Also in the circular cross section, the stresses and deflections are minimum, and from the results Factor of safety in the case with hemispherical end caps is 1.8*

Keywords: *storage tank, liquid oxygen storage tank, cryogenic tank, thin pressure vessel*

I. Introduction

Oxygen is the second largest component of the atmosphere, comprising 20.8% by volume. Liquid oxygen is pale blue and extremely cold. Although non-flammable, oxygen is a strong oxidizer. Oxygen is necessary to support life. Oxygen will react with nearly all organic materials and metals, usually forming an oxide. Materials that burn in air will burn more vigorously in oxygen. Equipment used in oxygen service must meet stringent cleaning requirements, and systems must be constructed of materials that have high ignition temperatures and that are nonreactive with oxygen under the service conditions. Vessels should be manufactured to American Society of Mechanical Engineers (ASME) codes and designed to withstand the process temperatures and pressures. Liquid oxygen is a cryogenic liquid. Cryogenic liquids are liquefied gases that have a normal boiling point below –130°F (–90°C). Liquid oxygen has a boiling point of –297°F (–183°C). Because the temperature difference between the product and the surrounding environment is substantial—even in the winter—keeping liquid oxygen insulated from the surrounding heat is essential. The product also requires special equipment for handling and storage. Oxygen is often stored as a liquid, although it is used primarily as a gas. Liquid storage is less bulky and less costly than the equivalent capacity of high-pressure gaseous storage. A typical storage system consists of a cryogenic storage tank, one or more vaporizers and a pressure control system. The cryogenic tank is constructed, in principle, like a vacuum bottle. There is an inner vessel surrounded by an outer vessel. Between the vessels is an annular space that contains an insulating medium from which all the air has been removed. This space keeps heat away from the liquid oxygen held in the inner vessel. Vaporizers convert the liquid oxygen into a gaseous state. A pressure control manifold then controls the gas pressure that is fed to the process or application. Vessels used in liquid oxygen service should be designed according to ASME codes for the pressure and temperatures involved. Piping design should follow similar codes, as issued by the American National Standards Institute (ANSI). A pressure control manifold controls the pressure at which the gas is fed to the process. Processes that use oxygen as a liquid do not require the vaporizers and pressure control manifold. A typical installation (see Figure) includes a tank, a vaporizer, and a pressure control manifold. Tanks may be spherical or cylindrical in shape. They are mounted in fixed locations as stationary vessels or on railroad car or truck chassis for easy transportation. Sizes range from 2 to 1590 K Litres, and all tanks are powder- and vacuum-insulated in the annular space. Tanks are equipped with various circuits to control product fill, pressure buildup, pressure relief, product withdrawal, and tank vacuum. Tanks are designed to ASME specifications for the pressures and temperatures involved.

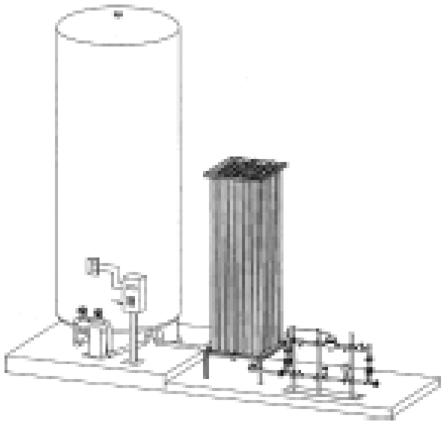

Figure 1: A typical cryogenic storage tank with vaporizer and other components

II. Physical And Chemical Properties

Chemical formula	O_2
Molecular Weight	31.999
Boiling Point @ 1 atm	-183 ^oC
Freezing Point @ 1 atm	-218.8 ^oC
Critical Temperature	-118.4 ^oC
Critical Pressure	729.1 psi (49 bar apprx)
Density, Liquid @ BP, 1 atm	71.23 lb/scf
Density, Gas @ 68°F (20°C), 1 atm	0.0831 lb/scf
Specific Gravity, Gas (air=1) @ 68°F (20°C), 1 atm	1.11
Specific Gravity, Liquid (water=1) @ 68°F (20°C), 1 atm	1.14
Specific Volume @ 68°F (20°C), 1 atm	12.08 scf/lb
Latent Heat of Vaporization	2,934 Btu/lb mole
Expansion Ratio, Liquid to Gas, BP to 68°F (20°C)	1 to 860

Table 1: Properties of Liquid Oxygen

III. Pressure Vessel

However the construction of a liquid oxygen storage tank will be as same as pressure vessel with special considerations like cryogenic temperature etc. Pressure vessel is a closed container designed to hold gases or liquids at a pressure substantially different from the ambient pressure. The pressure vessel may be thin or thick. When ratio of the plate thickness to mean radius of the pressure vessel is less than 1/15 then the pressure vessel is termed as a thin pressure vessel, otherwise, a thick pressure vessel. Pressure vessels are used in a variety of applications in both industry and the private sector. They appear in these sectors as industrial compressed air receivers and domestic hot water storage tanks.

3.1. Classification of pressure vessel

There are two different factors in the classification of pressure vessel

According to thickness

1. Thin cylinder
2. Thick cylinder

According to end cap

1. closed ended
2. open ended

If ‘t’ smaller than of ‘d’ then it is said to be as thin cylinder. Where t/d must be less than 0.1 or t/d< 0.1.So 10% of the internal diameter, if the ratio exceeds then the cylinder is said to be a thick cylinder.

3.2. Selection of Pressure Vessel

The first step in the design of any vessel is the selection of the type best suited for the particular service in question. The primary factors influencing this choice are,

- The operating temperature and pressure.
- Function and location of vessel.
- Nature of fluid & Necessary volume for storage or capacity for processing

It is possible to indicate some generalities in the existing uses of the common types of vessels. For storage of fluids at atmospheric pressure, cylindrical tanks with flat bottoms and conical roofs commonly used. Spheres or spheroids are employed for pressure storage where the volume required is large. For smaller volume under pressure, cylindrical tanks with formed heads are more economical.

3.3. Selection of Material for storage tank

Depending upon the operating temperature and pressure of a storage tank, we have to select appropriate material for it. As per ASME SEC VIII DIVISION 1 we prefer to select the material for this Liquid oxygen storage tank is ASTM(American standard for Testing of Materials) A 240 grade Stainless steel 304L. Austenitic Stainless steel and with low carbon content is a low temperature resistant and corrosion resistant reasonably strong and tough, weldable, bad thermal conductor steel which is most preferable for storing cryogenic liquids.

3.4. Chemical composition of SS304L

Table 2: Chemical composition of SS 304 & SS 304L

	SS 304	**SS 304L**
CARBON	0.08 MAX	0.030 MAX
NICKEL	8.0 - 10.5	8.0 – 12.0
CHROMIUM	18.0 – 20.0	18.0- 20.0
MANGANESE	2.00 MAX	2.00 MAX
PHOSPHOROUS	0.045 MAX	0.045MAX
SULPHUR	0.030 MAX	0.030 MAX
SILICON	0.75 MAX	0.75 MAX
NITROGEN	0.1 MAX	0.1 MAX

3.5. Mechanical Properties of SS 304L

Table 3: Mechanical properties of SS 304 & SS 304L

	SS 304	**SS 304L**
ULTIMATE TENSILE STRENGTH	515 MPA	485 MPA
0.2% YIELD STRENGTH	205 MPA	170 MPA
ELONGATION % IN 2" (50.8MM)	40	40
HARDNESS, ROCKWELL B	92	92

3.6. Effects of Alloying Elements on Steels

Nickel: This has the impart of increasing the strength and toughness of the steel. Generally it combines higher strength level and hardness with enhanced elastic limit, good ductility as well as high resistance to corrosion and creeping at elevated temperatures.

Chromium: Generally the addition of this element improves hardness, strength and elastic properties. The great purpose is that it serves to impart corrosion resistance to steel both at low and high temperatures. Steels combined with chromium and nickel is extensively used in the automobile and oil/gas industries.

Manganese: It improves the strength of the steel be it in the hot rolled or heat treated condition. It is usually added in small amounts. The main uses of manganese steels are in machinery parts serving heavy wear operations as in gears and splines. These steels come in the cast state and are generally ground to finish.

Silicon: They are like nickel steels. Possess high elastic properties compared to ordinary carbon steels. Steels combined with silicon are employed in services requiring resistance to corrosion.

Tungsten: It inhibits the growth of grains, it increases the depth of hardening of quenched steel and stabilizes the property of hardness even when heated to become red hot. Tungsten combined steels are used in the machine tool industry as well as some aspects of the electrical industry.

Vanadium: Vanadium aids in obtaining a fine grain structure in the steel. Addition of small amount of vanadium (about 0.2%) achieves quite a high increase in tensile strength and elastic strength in low and medium grade carbon steels without appreciable reduction in ductility.

Molybdenum: A very small amount of molybdenum is added with chromium and manganese to form molybdenum steels. They possess extra high tensile strength and have anti-creep properties at high temperatures, thus the steel helps to stabilize chrome nickel steels at elevated temperatures. Steels that must be resistant to creep at high temperatures must contain molybdenum, silicon and chromium. These impart on their resistance to oxidation and scaling at high temperatures.

3.7. Welding of a Dished ends with cylindrical vessel

A cylindrical vessel and also hemispherical end caps with the vessel are welded by Shielded metal arc welding (SMAW). A TIG welding machine with tungsten electrode and ER308L filler wires are used in welding and High purity argon is used as a Shielding gas. Filler wire is selected as per ASME SEC II PART C and from the Schaeffler Diagram. The Schaeffler diagram provides information on the welding properties of the various types of microstructure, as a function of what alloying elements they contain. Chromium equivalent is calculated using the weight percentage of ferrite stabilising elements and Nickel equivalent is calculated using the weight percentage of austenite stabilising elements. By entering the Ni-equivalent over the Cr-equivalent for stainless steel into a diagram according to Schaeffler one is able to find the content of martensite, austenite and ferrite in the resulting microstructure

3.8. Speciality of SS 304L over SS 304 and Sensitization

If we observe and compare carbon content in both the SS 304 and SS 304L metals, it is very less in SS 304L which helps us avoid sensitization and Inter Granular Corrossion. In nickel alloys and austenitic **stainless steels**, where chromium is added for corrosion resistance, the mechanism involved is precipitation of chromium carbide at the grain boundaries, resulting in the formation of chromium-depleted zones adjacent to the grain boundaries this process is called **sensitization**.

2.8. CATIA Design of Cryogenic Pressure Vessel

Commonly referred to as a 3D Product Lifecycle Management software suite, CATIA supports multiple stages of product development (CAX), including conceptualization, design (CAD), engineering (CAE) and manufacturing (CAM). CATIA facilitates collaborative engineering across disciplines around its 3D experience platform, including surfacing & shape design, electrical fluid & electronics systems design, mechanical engineering and systems engineering. CATIA facilitates the design of electronic, electrical, and distributed systems such as fluid and HVAC systems, all the way to the production of documentation for manufacturing. CATIA enables the creation of 3D parts, from 3D sketches, sheet metal, composites, molded, forged or tooling parts up to the definition of mechanical assemblies. The software provides advanced technologies for mechanical surfacing. It provides tools to complete product definition, including functional tolerances as well as kinematics definition. CATIA provides a wide range of applications for tooling design, for both generic tooling and mold & die.

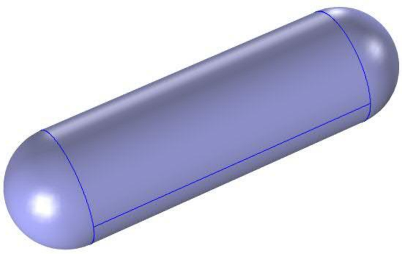

Figure 2: 3D model of simple solid wall pressure vessel

Figure 3 : Storage tank of LO_2

2.9. Design Calculation

A liquid oxygen storage tank consists of two layers of vessels with vacuum insulated and perlite powder in space between them at a vaccum rate less than $2X10^{-2}$ mbar. However we will consider only inner vessel for our design purpose because of its direct contact with high pressure and cryogenic temperature liquid. Due to internal pressure and small thickness of the shell is considered as a "thin" cylinder. In general, the physical criteria are governed by the ratio of diameter to wall thickness and the shell is designed as thin cylinder, if its wall thickness doesn't exceeds one-tenth of the inside diameter.

Input Data:

Design pressure p - 1.765 N/mm^2 (18 kg/cm^2)
Design Temperature T - -183 ^oC
Design Code - ASME SEC.VIII Division -1
Inside radius of tank R - 800 mm
Inside Diameter of vessel D - 1600mm
Joint Efficiency J - 1
Safety Factor F.S - 1.8
Corrosion Allowance C.A - 3.0 mm

The design of solid pressure vessel includes:

a. Design of vessel thickness.
b. Design of dished ends thickness
c. Calculation of Hydrostatic Test pressure.
d. Calculation of Bursting pressure.

(a) Design of vessel thickness in calculated from the equation:

$$t = R\left[\sqrt{\frac{SJ+P}{SJ-P}}-1\right]+C.A$$

$$t = 800\left[\sqrt{\frac{(269.4X1+1.765)}{(269.4X1-1.765)}}-1\right]+3.0$$

$= 13.552mm$

(b) Thickness of the dished end is given by:

$$t_d = \left[\frac{PR}{(2SJ-0.2P)}\right]+C.A$$

$$t_d = \left[\frac{1.765X800}{(2X269.4X1-0.2X1.765)}\right]+3.0$$

$= 5.62mm$

Adopted Thickness of the dished end t_d=13.552mm

(c) Calculation of Hydrostatic Test Pressure:

Hydrostatic pressure is taken as 1.3 times design pressure.
P_H = 1.3 X Design Pressure
= 1.3 x 1.765
P_H = 2.3 N/mm^2 (23.4 kg/cm^2)
Stress developed during Hydrostatic Test :

I. In vessel

$$t = R\left[\sqrt{\frac{SJ+P}{SJ-P}}-1\right]$$

$$13.552 = 800\left[\sqrt{\frac{(SX1.0+2.3)}{(SX1.0-2.3)}}-1\right]$$

S = 136.8 N/mm^2

The stress developed (136.8 N/mm^2) is less than the allowable stress value (216.9 N/mm^2) which is 90% of the yield stress.

II. In Dished end

The stress developed inside the Dish is given by the equation,

$$S_{Hd} = \left[\frac{PHXR+0.2PHt}{2Xt}\right]$$

$$S_{Hd} = \left[\frac{2.3X800+0.2X2.3X13.552}{2X13.552}\right]$$

$$= 68.117 \text{ N/mm}^2$$

The stress developed (68.117 N/mm^2) is less than the allowable stress value (216.9 N/mm^2) which is 90% of the yield stress.

(d) Calculating of Bursting pressure:

Ultimate tensile strength of material = 485 N/mm^2

K = Outer Diameter / inner diameter

= 1627/1600 = 1.017

Bursting pressure is calculated as per Lame's method

$$P_B = \left[U.T.S\,X\,\frac{K2-1}{(K2+1)}\right]$$

$$= 8.116 \text{ N/mm}^2$$

Stress developed during Bursting Test :

Stress developed inside the Dished ends is given by equation

$$SB_d = \left[\frac{PB\,X\,R+0.2\,X\,PBX\,t}{2Xt}\right]$$

$$SB_d = \left[\frac{8.116\,X\,800 + 0.2\,X\,8.116\,X\,13.552}{2X13.552}\right]$$

$$= 240 \text{ N/mm}^2$$

Stress developed(240 N/mm^2) is less than allowable stress value 241 N/mm^2 (which is 100%yield stress). **Hence the Design is safe.**

IV. Conclusions

- ✓ The most stable stainless steels for the Liquid oxygen storage tank which has aggressive corrosive environment are the stainless steels with higher quantities of nickel, chromium and the SS type substituted with low carbon content which help in stabilization of the austenite structure and to avoid Inter Granular corrosion at the weldments.
- ✓ We can avoid corrosion of piping and vent lines by using low carbon stainless steels.
- ✓ The cryogenic valves which are using in the present design also can be replaced with low carbon steels.
- ✓ The present work can be extended for the study of Inter granular corrosion.

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