Design and Calculation of a Liquid Nitrogen Storage Vessel using ASME Code

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Abstract— In this work study has been conducted and design of cryogenic storage wall for liquid nitrogen storage vessel using ASME code is prepared. The design mainly concerned with two chambers mounted concentrically out of which one experiences internal pressure and other experiences external pressure with proper fixture and connecting arrangements. The operating pressure is 0.1 MPa for both inside nitrogen storage vessel and outside vacuum jacketed vessel. The present work explores the proper design guidelines for the design of storage vessel which can which can withstand the differential pressure with minimum heat loss using ASME codes and standards. ASME Boiler & Pressure vessel code (ASME Sec VIII, Div-1, Edition 2010, Addenda 2011) has been used for the design of the vessel and materials are selected as per ASME Sec II Part A & D (M), Edition 2010. The connecting pipes are designed as per the ASME B 36.10. Finite Element Analysis and experimental testing have been carried out for validation.

Keywords: ASME Code; Pressure Vessel; Finite Element Analysis; Cold Shock Test; Factor of Safety; Von Misses Stress, Hydrostatic Test, Cold Shock Test

I. INTRODUCTION

Generally, pressure vessels are in the system of cylinders, spheres, ellipsoids or a combination of these. Liquid nitrogen storage vessels are composed of a complete nitrogen containing chamber with flange rings covered with vacuum jacketed evacuated chamber, fasteners are used for connecting mating parts. When thickness is insignificant in contrast with a mean diameter (R_m / t > 10), vessels are designated as membrane and the stresses are developed due to the loading are called as Membrane stresses which are maybe tensile or compressive in nature and these stresses are sup- posed to be constant across the vessel wall [2]. The membrane or wall of the pressure vessel is sup- posed to have no confrontation to bending. When the wall of the vessel, offers resistance to bending, bending stress also developed in addition to the membrane stresses, thus in an intricate shape vessel loaded with internal pressure, the membrane stress does not give the satisfactory idea about the true stress- strain condition. Other factors like the effect of supports, types of end covers used for closing the vessel, nozzles, thickness variation and external attachments like piping system all cause uneven stress distribution in the pressure vessel. ASME Boiler and Pressure Vessel provide a large factor of safety at the geometrical Discontinuity areas like openings, nozzle intersections, change of curvature, thickness variation etc.

The pressure vessel which is exposed to external or internal pressure, stresses are developed in the wall of the vessel. For thick vessel state of stress is triaxial with three principal stresses [2]

S_x = Meridional stress or longitudinal stress
S_y = Latitudinal stress or Circumferential stress
S_r = Radial stress

A. *Objective of the Study*

1) The optimal design of a pressure vessel which can withstand the specified pressure in accordance with ASME Boiler and Pressure Vessel Code.
2) Vacuum chamber should achieve a high order evacuated vacuum environment of for increasing the mean free path of the molecules.
3) Proper thermal design to minimize the heat loss due to evaporation of liquid nitrogen.
4) Complete assembly should withstand the hydrostatic test, leak test in vacuum condition and cold shock Test

II. LITERATURE REVIEW

The broad objective of this chapter is to provide background information relating to the pressure vessel study of the literature. H.Mayer, H.L Stark and S. Ambrose [6] has studied the effect of parameters like stress intensity range and principal stress range on the fatigue life of the pressure vessel. S.V.Dubal and V.G Patil [7] has designed the horizontal pressure vessel supported on the saddle according to the guidelines given by ASME section VIII, Div 1 and Div 2. P. Petrovic [8] has studied the stress distribution in a cylindrical pressure vessel in which load applied at the free end of the nozzle using Finite Element Analysis. Impact of welding residual stress on the failure of the pressure was studied by M. Jeyakumar [9]. A comparative study between design of pressure vessel by analysis and by formula done by A.Th. Diamantoudis and Th. Kermanidis for high strength steel pressure vessels, [10] the identified areas of the survey include:

- Theory behind the pressure vessel design
- Approaches for design of pressure vessel as per ASME code.
- Factors causing pressure vessel failure

A. *Two Failure theories for Pressure Vessel Design*

1) *Maximum Principal Stress Theory*

According to this theory, breakdown or failure in a component is depends on the magnitude of induced max. principal stress due to complex loading. As per this theory failure or yielding starts in a component when the induced maximum principal stress equals to the yield stress of the material from the simple tension or compression test at elastic limit.. Maximum principal stress theory is used to predict failure in brittle materials.

2) *Maximum Shear Stress Theory*

According to this theory, failure or breakdown in a component material is depends on the intensity of the maximum shear stress induced due to complex loading. Thus, the failure starts at a point, when maximum shear stress at a point equals to the one half of the yield strength (F_y) from the uni axial tensile test. Both ASME section III and section VIII, Division 2 use the maximum shear stress criterion. Also this theory closely approaches to experimental results.

III. DESIGN

In general pressure vessels are designed in accordance with ASME Code. Design of nitrogen container mainly contains design of inner and outer vessel, design of front bolted flange, design of front cover flange and rear cover flange. ASME section VIII division 1 has been used during the design of each component. ASME section II has been used for the selection of material for each component.

A. Design of Nitrogen container

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1) Reference codes & Standards

Sr.No	Code	Description
1	ASME Sec VIII, Div-1, Edition 2010,Addenda 2011	Nitrogen Chamber
2	ASME Sec II Part A & D(M), Edition 2010	Materials
3	ASME B 36.10	Seamless Pipe

2) Design data for Nitrogen vessel

Sr.No	Description				
1	Design Code	ASME Sec VIII, Div 1, Edition 2010,Addenda 2011			
2	Working Pressure for Nitrogen vessel, Gauge (Internal)	1	bar	0.1	MPa
4	Design Pressure for Nitrogen vessel	2	bar	0.2	MPa
5	Design Temperature	313	K	40	^oC
6	Maximum Allowable Working Pressure	2	bar	0.2	MPa
7	Corrosion Allowance			0	mm
8	MDMT	77	K	-196	^oC
9	Radiographic requirement	Full			
10	Joint Efficiency	1			
11	Service	Liquid Nitrogen Chamber			
12	Hydrostatic Test Media	Water			

3) Design internal pressures calculation.

Density of Contents (Kg/m^3)	=	= 1000.00 (Assumed as water density)
Static Pressure Head	=	= g x 9.8067 x H
	=	=1000 x 9.8067 x 1615/1000
	=	=15837.82 Pascal
		= 0.015 MPa
Design Internal Pressure	=	= Design Pressure + Pressure due to Static Head
	=	= 0.2 MPa + 0.015 MPa
	=	0.215 MPa

4) Hydrostatic pressure calculation

Hydrostatic Test Pressure = Maximum allowable working Pressure x LSR x 1.3
LSR = Lowest Stress Ratio= 1
Hydrostatic Test Pressure for Nitrogen vessel = 0.2x1x1.3 = 0.26 MPa
Hydro test to be carried out in a horizontal position only.
Design of Outer cylindrical shell (Nitrogen Vessel) Thickness under Internal Pressure [Ref: UG-27 & Appendix-1]
The material selected for the outer cylindrical shell is SA 240 TYPE 316. Assumed thickness (t) of the vessel is 5 mm. considering the mill Tolerance of 0.19 mm from the UG 16 (c), table A 3.5, SEC II Part A,
So effective thickness is 5 – 0.19 = 4.81 mm.
Considering thinning due to rolling = 4%
Reduction in thickness due to rolling = 4.81- (0.04x4.81) = 4.61
Internal design pressure (P) = 0.21 MPa
Maximum allowable stress from section II part D (S) = 115 MPa
The outer diameter of the vessel (D_0) = 1000 mm
Inside diameter of the vessel (D) = 990 mm
Longitudinal joint efficiency from UW-12 = 1
The minimum required thickness (t) as per ASME Appendix -1 is given by:
t = PR/ ((SE)-(0.6P))
= 0.21x500 / (115x1 + 0.6x0.21)
= 0.896 mm
But according to ASME Code, UG-16 (b) the minimum thickness of the shell must be 1/16 inch excluding the corrosion allowances i.e. 1.5 mm.
Since required thickness is less than the provided thickness, i.e. 1.5 < 4.61 mm, so provided thickness is adequate.
Design of inner cylindrical shell (Nitrogen Vessel) Thickness under external Pressure [Ref: UG-28 (c) (1)].
The material selected for the outer cylindrical shell is SA 240 TYPE 316L. Assumed thickness (t) of the vessel is 5 mm. considering the mill tolerance of 0.19 mm from the table A 3.5, SEC II Part A,
So effective thickness is 5 – 0.19 = 4.81 mm.
Outer diameter of the vessel (D_0) = 535 mm
Inside diameter of the vessel (D) = 525 mm
Length of the vessel = 900 mm
The ratio of length of the vessel to the outer diameter of The vessel = L/Do = 900/535 = 1.68
The ratio of the outer diameter of the vessel to the thickness of the vessel = Do/t = 535/4.81 = 111.22 From the ASME code Fig- g, Section II, Part D, Factor (A) = 0.0007

From the ASME code fig-HA-4, for SA 240 TYPE 316L, Factor (B) = 60

The allowable external pressure working pressure (Pa) from the code is given by: = 4B (3*(Do/t))

= 4 x 60 / (3x (535/4.81))

= 0.72 MPa

The actual working pressure is 0.1 MPa which is lower than the allowable external pressure of 0.72 MPa so the provided thickness (4.81 mm) is adequate.

B. Thermal Design of Nitrogen Storage Container

Proper thermal designing in cryogenic systems is the most challenging design for cryogenic apparatus like liquid nitrogen storage containers, which directly impacts on the performance during its operation. The thermal design should be such that heat loss will be minimized as much as possible and it should be in the acceptable range. The heat transfer basically occurs in three ways; Conduction heat transfer through solids Convection - heat transfer through liquids and gases Radiation – heat transfer through space Heat transfer through conduction can be more precisely calculated, but in the case heat transfer through convection and radiation a reasonable approximate estimate can be done.

In liquid Helium or Nitrogen storage container, it needs to have the least amount of heat load com- ing in to that storage container (at 4.2 K or 77K). The maximum contribution of heat load that can be transferred in to the storage container is due to natural convection from the atmospheric air which is at 300 K, hence to reduce the heat load due to natural convection we need to evacuate the space between vacuum chamber and the nitrogen storage chamber. The space can be evacuated using roughing pump and the turbo pump to create a vacuum in the range of 10^{-5} mbar. The number of gas molecules reduces at vacuum condition which increases the mean free path of the gas molecules, approximately at 10^{-4} mbar, mean free path is about 100 cm which is more than the dis tance between the surfaces which leads to reduce heat load to few mill watts at vacuum of 10^{-5} mbar. Multilayer insulation, which consists of highly reflective aluminum sheets are intended to re- duce radiation heat transfer. Insulator like G10 material is used as the separators between the nitro- gen chamber and the vacuum chamber for reducing the conduction heat load.

In nitrogen container vessel, total heat loss is mainly due to the conduction, radiation only. Heat loss due to the natural convection is negligible due to evacuate the vacuum chamber. The conduction heat transfer occurred due to G10 separators and due to neck region of cylindrical surface. Similarly radiation heat transferred due to both flat end of the vacuum chamber, due to cylindrical surface of the vacuum chamber, due to flat end of the neck and due to cylindrical surface of the neck.

IV. CAD AND FINITE ELEMENT METHOD

After finalizing dimensions like the thickness of individual components from ASME design code, 2D concept layout drawing (as sown in fig. 6.1) has been developed in AUTOCAD software and consequently we developed the 3D model (as shown in fig. 6.2) in PRO-E software which was ex- ported to ANSYS for Finite Element Analysis purposes. Solid meshing was done on the full assembly and proper contact parameters were defined between the individual components. Separate material properties were assigned for different types of materials. Internal pressure has been applied to the inner nitrogen chamber and external pressure applied to the outer vacuum chamber.

In layout drawing twenty numbers of G10 separator used in between the nitrogen chamber and the vacuum chamber for the reduce conduction heat transfer. Some multilayer insulation having high reflectivity and low thermal conductivity are used to reduce radiation heat transfer. Multilayer insulation consists of the multiple layer of thin aluminum sheets of thickness 5 – 12 nm on Mylar film. Rear end covers are connected with the both nitrogen vessel and vacuum vessel through the welding process, whereas front end covers are attached with the vessels through the bolt joints. Front flange rings are also connected with vessel through weld joints.

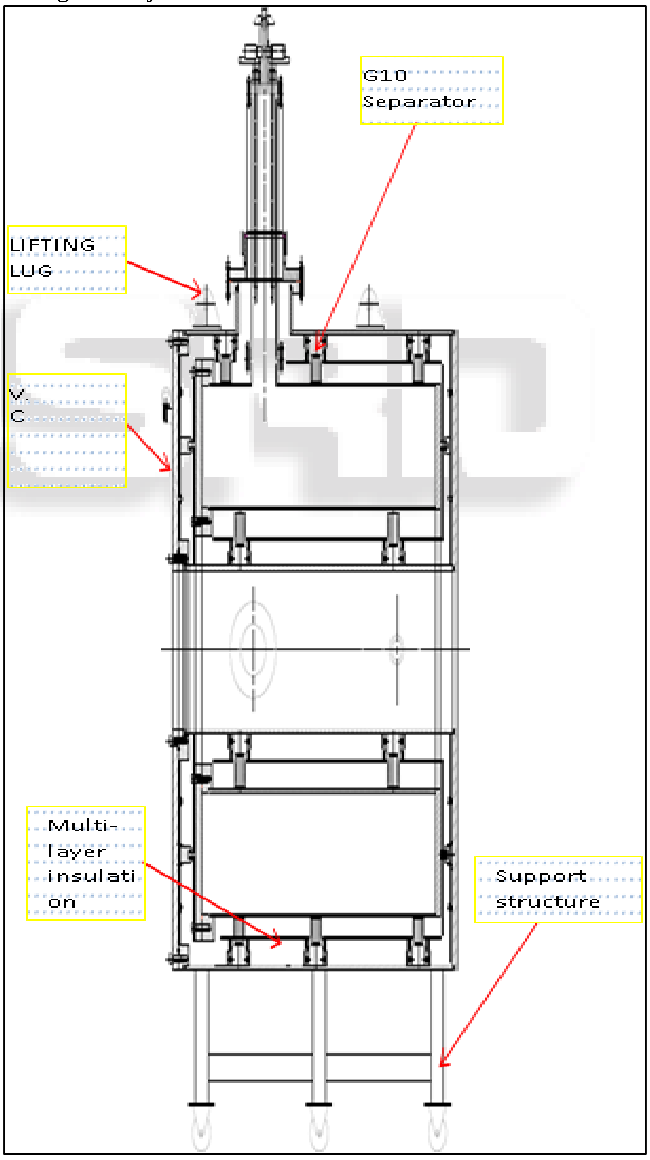

Fig. 6.1: 2D Layout concept drawing

V. EXPERIMENTAL TEST

Hydrostatic test and leak proof test are the two important tests which are to be carried out. Hydro- static test is required for ensuring the strength of the vessel during actual loading also to detect leakage. Hydrostatic test is done on the nitrogen vessel assembly as well as vacuum vessel assembly separately. For hydrostatic test, Nitrogen chamber assembly was pressurized at 2.6 bar for 30 minutes and vacuum vessel assembly was pressurized at 1.3 bar for 30 minutes. For ensuring the effectiveness of leak proof joints, leak test was carried out. Roughing pump and turbo pumps are used for achieving a vacuum of order 10^{-5} in a vacuum vessel as shown in the fig. For minimum evaporation of liquid nitrogen.

Vacuum leak test setup

Vacuum pressure gauge

A. Fabrication and Assembly of Vessel

All the components are manufactured as per the part drawing. Dimensional tolerances and surface finish are the critical parameter during the assembly of the components. During assembly front cover end is connected with vessel through the bolt joints. Nozzles are connected with the vessel through the TIG welding and CF flanges are connected with the nozzle through the TIG welding. The following fig. shows the liquid nitrogen vessel during assembly.

Assembly of LN2 Storage Container.

VI. DISCUSSION AND CONCLUSIONS

- The liquid nitrogen storage vessel has been designed as per ASME Boiler and Pressure Vessel Code. ASME section II used for material selection, section V used for nondestructive testing like weld defect detection, section VIII division 1 used for design of components and section IX used for welding and brazing qualification.
- Finite Element Analysis of the assembly was carried out by ANSYS workbench and found that maximum Vonmises stress was 102 MPa which is well below the yield limit of the specified material, thus the design is safe.
- Total heat load transferred to the nitrogen chamber is minimized by implementing multilayer insulation for the reduction of radiation heat transfer, G10 insulator separator for reduction in conduction heat transfer and a evacuated chamber of order 10^{-5} mbar for the reduction in convection heat transfer. The total heat load on the nitrogen chamber is 16.58 watts, which shows the effective thermal design of the nitrogen storage container.
- Hydrostatic test was carried out through the water medium on both nitrogen chamber assembly and the vacuum vessel assembly separately for ensuring the strength against the specified load and it is found that both the assembly passed the required criteria.
- To find any defect in welding and material, cold shock test was carryout five times on the assembly and it is observed that there was no crack or defect found on the material as well as in welding.

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