Designing and Analysis of Cryogenic Storage Vessel

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February 27, 2021

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***Abstract* - Cryogenics is a scientific research that deals with extremely low temperatures Cryogenic storage vessels are used to store cryogens such as liquid nitrogen, liquid oxygen or liquid argon under the conditions required. In this paper, the materials used in the vessel are being addressed and analysed. There is a discussion of the various types of insulation systems. It addresses the construction of a large transportable vacuum insulated vessel and conducts stress and thermal analysis on it.**

Keywords—Cryogenics, Inner and Outer vessels, liquid nitrogen, Principal stresses, Von misses Stress

I. INTRODUCTION

A. Overview

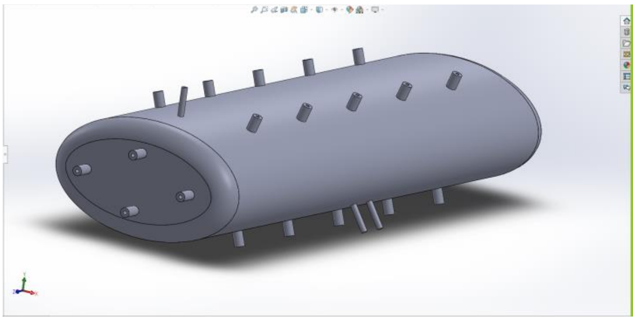
'Cryogenics' the term defined as the study of production and materials at a very low temperature ranging from -150℃ (123K) to as low as absolute zero. Cryogenic vessels generally have double walled cylindrical tanks with inner tank made up of stainless steel and outer of carbon steel sections painted with anti-corrosion primer and filled with an insulating material. The vessel is then evacuated to a high vacuum to achieve minimum evaporation losses. Considering the wide application and dangers associated with the cryogens, the need of storage of such liquids become prominent. In this paper, the cryogenic vessel will not only be sustainable but can be transported from one place to another, by truck equipped with hook-lift mechanism. Usually, the cryogenic vessel is used to store liquids like liquid oxygen (LOX), liquid nitrogen (LN, LIN), liquid argon (LAR), and liquid carbon dioxide (CO_2).

The project is aimed to study different materials and composites for the components of the vessel to make sure there is no leakage and minimal heat transfer is achieved. The different kind insulation systems in the cryogenic vessel is analysed. Stress and thermal analysis are being performed on the design. Manufacturing of these vessels requires special technical and sophisticated fabrication techniques.

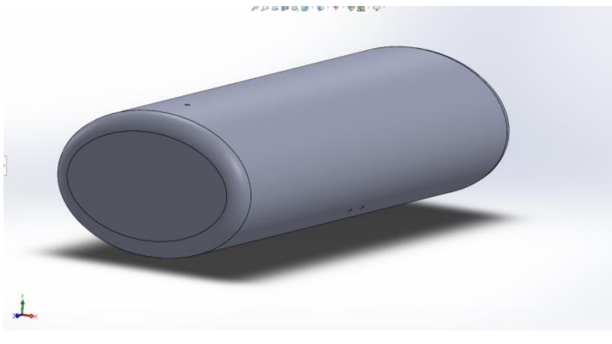
B. Vessel Components

The Cryogenic vessel may contain multiple layers of the desired material which shall be further selected, apart from the material of the layers of the vessel, it contains various types of gauges and valves. The main component which shall solve the aim is the insulation material which shall ensure that there is minimum or zero heat transfer between the inner content of the vessel and the atmosphere for maximum efficiency.

i) Inner Vessel: It is also known as product container. It is used to store the cryogenic fluid. The inner vessel must be constructed of materials compatible with cryogenic liquids. Therefore, stainless steel, aluminium alloys are preferred. The inner vessel should be a material which can take on sub cooled temperatures and any minor crack propagation should not occur.

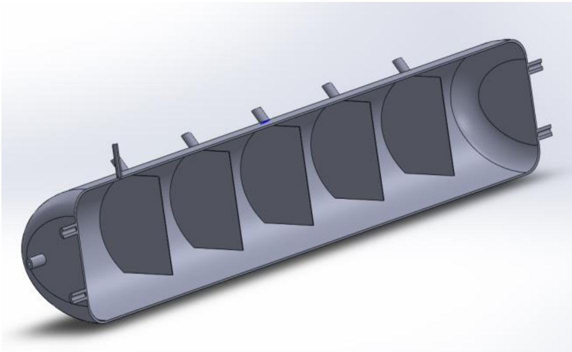


ii) Outer Vessel: It is also called as vacuum jacket. It holds the vacuum which is essential for the effectiveness of insulation & also acts as a wall which curtails the heat transfer with outside environment. For outer vessel, we can use carbon steel or copper alloys. The outer vessel should be made up of a thick durable material, ready to withstand any shocks which arise in case of drops or transportation. The outer vessel material should never deform, as it can damage the internal insulation system and leakages can occur due to which multi-layer insulation or vacuum can get damaged.



iii) Surge plates:

There are some thin plates inside the inner portion of the inner vessel that are known as surge plates. They reduces the effect moving waves of cryogenic liquid while the movement of the truck which eventually decreases heat interaction between the liquid and walls of inner vessel increasing the efficiency. The outline of the surge plates matches the shape of the vessel, but terminates at the top and bottom of the horizontal edges.



iv) Insulation System:

The space between the inner and outer vessel is for the insulation. The efficaciousness of the cryogenic vessel depends on this system and hence it is very important parameter that should be considered in the design of the cryogenic storage vessels. The main and the most effective insulation system is vacuum insulation. The air between the gap of the vessel is sucked out with the help of air separation unit and the vacuum is achieved. Though being the most effective insulation system, it can't be commercialised as it is very expensive. Nevertheless, for small scale and for local use, there are few other systems which are cheaper and can be effective if properly inculcated. Few of them are mentioned below,

i) Multilayer insulation system

ii) Powder insulators

iii) Using inert gases

iv) Fabric Materials

There are two types of insulation methods for cryogenic vessels: (A)Non-vacuum insulation (B)vacuum insulation. (A)Non-vacuum insulation uses unique materials which has a very low value of heat conductivity. A good example of such a material is the insulation polyurethane foam, whose heat conductivity is 0.028 W/m·K., The most widely used insulation system is vacuum insulation. Since vacuum has almost no heat conductivity the efficiency of the system is very high . This is why a vacuum insulated system is selected.

(B) Vacuum insulation method consists of creating a vacuum between the two surfaces which are at different temperatures. Also, special materials can be added within the space between the two vessels to obtain lower heat conductivity and to also get a load carrying capacity that separates the vessels. There are two different methods depending on the added material. The first method is denoted multi-layer insulation (MLI) , and is also known as super insulation (SI). The second method is the expanded perlite insulation.

Multi-layer insulation consists of creating many radiation shields (normally aluminium foil) stacked in parallel as close together as possible without having actual contact. It typically contains about 60 layers per inch. MLI structures are anisotropic by nature, which makes it difficult to analyse them. It is also very sensitive to mechanical compression and edge effects, so careful attention to detail during all phases of its installation is mechanically required. Heat conductivity is not as good in practice as it is in theory. Their always will be heat interaction between vessel and atmosphere.

In MLI, each layer is isolated from the other by spacer material such as polyester, polyamide or Mylar. Aluminium foil is carefully wrapped around the container in such a way that the entire surface of the inner vessel is covered. Spacer material is placed between the layers to completely prevent the separate coverings of foil from making contact. If they are in contact, a thermal short circuit would occur and will result in increase the heat transfer. The layers can be applied manually as blankets. These are hand cut to fit and are wrapped over the vessel and vessel ends. Tape of low out-gassing properties is then used to hold the blanket layers in place.

Multi-layer insulation can only be used if the vacuum pressure is below 1 mTorr, which is approximately 1 mbar. To obtain this vacuum, pumping for a long time is generally required along with heating and purging cycles. Chemical gettering materials are required to absorb the out-gassed molecules to maintain the vacuum over extended periods.

On the other hand, perlite insulation that is suitable for vacuumed cryogenic vessels has a low thermal conductivity throughout a wide range of temperatures, pressures, and densities [8]. The working pressure for perlite is about 10 mTorr, which is approximately 10 mbar. Perlite is relatively low in cost, high availability, easy to handle and install and does not shrink, swell, warp or slump in comparison to other added materials. It is also non-combustible.

Perlite must be dry. During operating service, the normal moisture limit is 0.1 weight percent relative to the mass itself and this normal moisture limit greatly increases the pump-down time necessary to achieve the required vacuum. As a result, perlite must be fresh and packaged in moisture-proof bags or in a sealed tank.

There is a need for a vacuum insulation device that meets unique mechanical specifications. Usually, MLI is particularly susceptible to mechanical compression and edge effects. Since the vessel is loaded from a truck and unloaded, by using MLI, it is exposed to movements that will cause vital stresses on the unit. The multi-layer isolation system could be affected by these stresses, breaking its internal bonds between layers, which could decrease its insulation properties. For this reason, and also because of the high vacuum efficiency that MLI demands, this method of insulation is rejected for the vessel being constructed. Perlite insulation is, therefore, the best insulation solution for this project.

B. Vessel gauges and valves

The cryogenic vessel must be tracked and stabilized by various gauges and valves and these gauges have a precise measurement capacity, otherwise the slightest change in pressure variations will lead to trouble. Different parameters of the vessel are also tracked continuously. Evaporator, liquid container gauge, vacuum bursting disk, vent valve, pressure building valve, pressure building coil, pressure relief valve, pressure gauge, inner container bursting disk, liquid fill and withdrawal valve, economiser regulator, vent valve are the various gauges and valves used in the cryogenic vessel.
.
All these gauges and valves have the capability to work even at the higher pressure environments without any malfunction.

All these components are carefully monitored and regulated by computers. These computers are pre-programmed to take necessary counter measures to avoid any accidents. The components and computers are powered by a local battery unit.

The pressure gauge and the pressure relief valve are the critical components in the cryogenic storage vessel, since the pressure in the storage vessel should always have to be maintained at the necessary pressure level and if it is not maintained, the storage vessel can lead to leakage-causing failure.

II. PROBLEM DEFINATION

The main objective of designing the Cryogenic Vessel is to design such a vessel that can maintain extremely low temperatures. Inside the Cryogenic vessel, the extremely low temperature can generate minor crack propagation, further resulting in leakage failure in this crack propagation. The leakage can also be caused at the inlet/outlet due to the valve failure, so the best materials are to be used everywhere to ensure that no such failure takes place. When filling up or emptying the cryogenic vessel, the possibility of asphyxiation due to air displacement is also quite possible.

Due to the presence of hydrogen, oxygen or methane, there is always an inevitable fire hazard when working with them. The size and weight of the cryogenic vessel is another constraint to be kept in order, the main objective of which is that the vessel should also be accepted by industry. It is required to design an optimized end product that is easily portable.

III. INFORMATION ON VESSEL

3.1 Structure of Cryogenic Vessel

The cryogenic storage vessel is designed to have two distinct shells, one is referred to as the inner shell or product container and the other is referred to as the outer shell and is often referred to as the vacuum jacket. The air between the holes is sucked out with the aid of the air separation unit and it is vacuumed for better insulation. In some cases, various types of powders and gases are used for insulation, and the form of insulation is always independent of storage type and environmental conditions.

In large-capacity cryogenic tanks, multilayer insulation, powder isolators and fabric materials are used as insulators.

An insulation material used to separate vapor or air and other gases found in the atmosphere from cryogenic fluids. The efficacy of the storage vessel depends on the insulation, so the parameters that should be taken into account in the design of the cryogenic storage vessels are very significant.

And these two shells (tanks) are joined by a support block, these support blocks serve as stiffeners and help to maintain the vessel's structural stability by absorbing the stresses and holding the shell of the product secure.The storage vessel must be specially built in order to reduce heat transfer and withstand very low temperatures. Liquid oxygen, liquid nitrogen and liquid argon storage vessels are available commercially in different capacities. Depending on the site and usage requirements, the storage vessels can be vertical, circular, or horizontal.

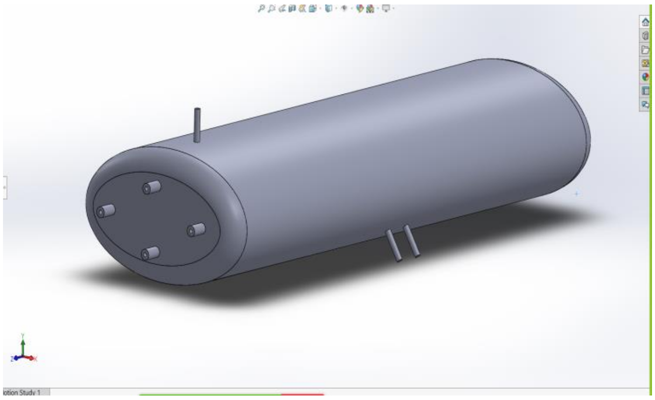
3.2 Cryogenic materials

Austenitic steels, stainless steels, double standardised and tempered fine grain nickel, steels, copper and aluminium are excellent materials that can withstand cryogenic temperatures.

Stainless steels
Austenitic stainless steels are suitable for cryogenic applications because, even at -269 ° C, they remain tough and ductile**.**

9% Nickel steels
9% of nickel steels are commonly known as ferrite steel, but this is austenitic ferrite and magnetite. The presence of austenitic has given excellent strength and resistance to brittle fracture.
The decline in ductility with a decrease in temperature below zero is very gradual and is above 25 Ft lbs (346 or 4.4 kg/cm2) at -200 °C because of chirpy v notch values. It has been commonly used in cryogenic equipment for storing and transporting liquefied gases such as nitrogen, me-thane and ethylene in the event of manufacturing proven protection and favorable cost.

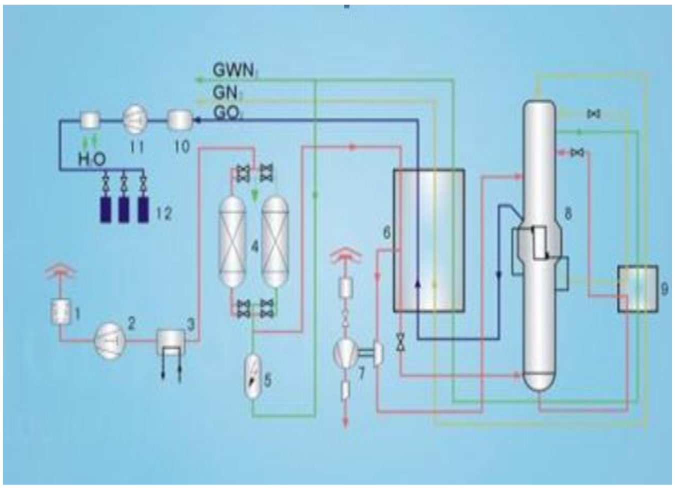
Extensive destruction experiments on tanks filled with liquid nitrogen have shown that quenching and tempering have not been beneficial and that treatment after welding has not been beneficial.



3.3 Air Separation Unit

The environment drains the oxygen out of it.In a five-stage compressor with an intercooler, the sucked air is compressed. Oil, humidity and carbon dioxide make up the compressed air. These impurities are liquefication obstructions because at lower temperatures carbon dioxide and moisture forms ice, which is barrier for flowing fluids. But you have to extract these impurities.

The compressed air passes through a filter that separates the compressed air from the oil. The compressed air which is free of oil is now pushed into a refrigerating device that cools the compressed air. It gathers these droplets in a separate vessel. A vessel consisting of molecular sieves that absorbs carbon dioxide present in the com-pressed air is now passing through the air.



This dry air is now passed through the post filter, which extracts additional impurities. The filtered air is passed through the post filter and any more impurities are removed. It sends the filtered air through the cold box.
This cold box is composed primarily of the following :

1) Heat exchangers
2) Exchange turbines
3) Inlet and outlet manifolds
4) A column composed of aluminium trays.

The compressed air is passed through a heat exchanger, which decreases the air temperature by around -140 °C. The cooling of air is allowed by passing the cold non condensable gases and gaseous nitrogen. The cold air in which the compressed air is expanded is pushed through the expansion turbine. The temperature is reduced to about -180 °C because of this expansion. The air is liquefied at this low temperature. The liquid air is then passed into a column consisting of top to bottom aluminium trays.
The evaporation of nitrogen and other gases takes place during this flood, and only oxygen is collected in the lower reservoirs. The liquid nitrogen at the top of the column is created. Because of this, it is possible to liquefy gaseous nitrogen by giving the liquid oxygen heat energy. The liquid oxygen has evaporated here. In the column, this liquid nitrogen is generated and pumped into the cold converter. Using this heat exchanger, which cools the incoming compressed air, the condensable gaseous nitrogen is transmitted, thereby generating and collecting liquid nitrogen and oxygen in the cold converter

Argon has an air content of 0.93 percent and has a boiling point between oxygen and nitrogen presented in both liquid nitrogen and liquid oxygen as impurity. The percentage of argon should be reduced in order to produce pure liquid nitrogen. Using the other column, which separates argon, will decrease this.

IV. LITERATURE SURVEY

The different properties like temperature, pressure of cryogens are obtained from [1]. The properties of various materials, alloys, composites for components of cryogenic vessel are from [2]. Truck specifications and design of hook lift mechanism can be obtained from [3] and [4] respectively. The heat transfer between different surfaces and stress and thermal analysis are obtained from [5] and [6] respectively.

V. METHODOLOGY

Flow of our project: a) Research on Cryogenic Vessel
b) Design and analysis
c) Manufacturing

Research Phase: The study of various materials and the choice of materials for cryogenic vessels. Analysis of traditional and experimental systems of insulation..

Design Phase: Design of the cryogenic vessel using CAD, Solidworks like software.

Analysis Phase: Stress and thermal analysis using Ansys, Catia like software.

Manufacturing phase: Once the material for our inner and outer vessels we can start with the manufacturing**.**

VI. CALCULATIONS

The following are required properties for liquid nitrogen storage applications:

•Tensile and shear moduli
•Thermal conductivity
•Surface emissivity
•Vacuum characteristics
•Low thermal contraction co-efficient
•Method of fabrication
•Hot and cold tensile and yield strengths
•Availability in standard shape and size
•Economical

The materials which can be used to build the vessel are:
A) Carbon steel (for outer shell only)
B Low alloy steel and different grades
C) Stainless steel and different grades
D) Aluminum and different grades
E) Copper and different grades
F) Nickel alloys (annealed)

A) Inner vessel design: According to the ASME Code, Section VIII, the minimum thickness of the inner shell for a cylindrical vessel should be determined from

$$t_i = pD_{ii}/(2*S_a*E_w - 1.2p) \quad (1)$$

Where,
t_i = minimum thickness of inner vessel
p = design internal pressure
D_{ii} = inside diameter of inner shell
S_a = allowable stress
ew = weld efficiency

B) Outer vessel design: The outer vessel would withstand only the ambient pressure acting on it, so that due to undue stress it would not collapse, but from the point of view of elastic instability it would fail (collapsing or buckling).For insulation, the outer vessel
functions as a vapor barrier. The critical pressure according to the ASME section VIII is given as following

$$p_c = 4 \times p_a \quad (2)$$

p_a = atmospheric pressure, kpa

The collapsing or critical pressure for a long cylinder exposed to external pressure is given by,

$$P_c = 2E(t_o/DO_o)^3/(1-\mu^2) \quad (3)$$

Where,
E = Young's modulus of shell material
t_o = minimum thickness of outer Shell
DO_o= outside diameter of outer shell
μ = poisson‟s ratio for shell material

V. RESULTS

As a team for this project, our aim is to research various materials that can be used to manufacture the inner, outer vessels of the cryogenic storage vessel and create an optimal design of a large-scale model that can be transported by a hook-lift mechanism fitted truck. We can accomplish this with the use of software such as CAD, Solidworks, Ansys and hope to reproduce this to create a small model for the above-mentioned concept.

VI. CONCLUSIONS

The potential scope and research for this project is to develop a cheaper but more efficient insulation system used in the vessel (as the systems currently available are very expensive) and to make the transfer of heat as minimal as possible by insulating various alloys and composites.We intend to investigate the feasibility of the above statements and create an optimized design.

VII. ACKNOWLEDGEMENT

It is with immense pride and pleasure to express my sincere gratitude to my guide Prof. Krishna Gaikwad, Professor in Mechanical Engineering Department of Thakur College of Engineering, Mumbai

VIII. REFERENCES

[1] Data book for cryogenic gases and equipment by CHART industries.
[2] Wigley, D.A., The mechanical properties of Materials at Low Temperatures, Plenum Press, New York, 1971, pp 311-363.
[3] Truck specifications, [accessed 2010-03] http://datasheets.volvotrucks.com/default.aspx?market=great%20britain HYPERLINK
[4] Hook-lift mechanism specifications, [accessed 2010-03] http://www.cayvol.com/
[5] O.Khemis. M.Boumaza,M.Ait Ali,M.X.Francois (2004) "Measurement of heat transfers in cryogenic tank with several Congratulations".
[6] S.M.A Khan, Stress distributions in a horizontal pressure vessel and the saddle supports, International Journal of Pressure Vessels and Piping 87 (2010) 239- 244.
[7] Swedish standards, *SS-EN 13530-1: Cryogenic vessels - Large transportable vacuum insulated vessel; Part 1: Fundamental requirements.* Swedish Standard Institute, 2003.