Parametric Study of Cryogenics Storage Vessel for Different Materials

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Abstract—Cryogenic Vessels are designed for storage and transportation of liquid gases at sub-zero temperatures. Manufacturing of such cryogenic tanks requires special technical knowledge and sophisticated fabrication techniques. Universal has developed the necessary technology. The design and construction of storage Dewars for biological specimens. Biological requirements of Dewar design are of prime importance and these have to be considered alongside the normal cryogenic requirements such as insulation, suitable materials etc. The liquid nitrogen storage systems are widely used for long term preservation of a range of microorganisms. Strains are stored in ampoules immersed in nitrogen or held in its evolving vapor. In this paper I had worked on the comparative design of storage tank made up of two different materials i.e. stainless steel and aluminium used as inner shell of cryogenic vessels. This paper includes design procedure of cryogenic storage vessel as per ASME code. This also contain results of different properties i.e. heat in-leak, boil off rate of vessel by taking aluminium and stain less steel as inner shell of vessel.

Key words—Cryogenic storage vessel, Boil off rate, Heat in leak, Perlite Insulation, Multi-Layer Insulation.

I. INTRODUCTION

The design of low temperature apparatus calls for attention to certain special problems. Such apparatus consists mainly of heat sinks and heat barriers and most constructional problems are related to questions of the thermal insulation. It is at very low temperature that such problems become sufficient at low temperature, to produce a big change in the physical state of cryogens.Thermal insulation may involve precautions against radiation, the use of high vacuum jackets and the use of special materials of low thermal conductivity and emissivity. Shields can deal with radiation readily. With the increased use of cryogenic fluid like liquid nitrogen and liquid oxygen for biological and industrial applications, the use for suitable storage and transporting vessels also increased. Low boiling point of all these fluids mandates the need for well insulated system to prevent excessive heat in-leak during storage and transfer of cryogenic liquids. Other consideration concerns the overall weight, size and transportation easy and cost. In this paper design procedure of storage vessel is explained and also designed storage vessel made up of stainless steel and aluminium as inner vessel. Also compare its properties and suggest suitable material for storage vessel.

A. Components of Storage Vessels

Storage vessel mainly contains inner vessel, outer vessel, inner and outer stiffening rings, insulations, piping, suspension system etc.

1) Inner Vessel

Inner vessel is inner most part of the storage vessel. It is surrounded by cryogenic fluids. It also called product container. The material used for construction of inner vessel must be sustainable to low temperature. The material used for inner vessel is generally stainless steel, aluminium etc.

2) Outer Vessel

Outer vessel is used for covering the inner vessel. It is also known as vacuum jacket. It contains the high vacuum necessary for the effectiveness of the insulation and acts as a vapor barrio for the insulations. Outer vessel is generally made up of carbon steel or low alloy steel and composite fibrous material.

3) Stiffening Rings

Stiffening rings are used for both inner and outer vessel. It is used to support the weight of inner vessel and cryogenic fluid. Also it is used to hold the outer vessel shell circular.

4) Insulation

The space between inner and outer vessel is filled with insulation. It is used to prevent the heat-in leak from ambient temperature to cryogenic temperature. Generally insulation is selected on the basis of thermal conductivity. The boil of rate of cryogenic fluid is depending on insulation only so it is important component of storage vessel.

5) Suspension System

The suspension system must be used to support the inner vessel within the outer vessel. A thermally poor suspension system can nullify the use of well-designed insulation.

6) Piping

Piping is necessary to filled and remove the liquid from the vessel and to vent vapor from the vessel. The minimum wall thickness of piping should be designed on the basis of internal pressure.

7) Safety Devices

Safety devices are used to relieve the overpressure so that damage to the inner vessel is avoided. Minimum safety device used on storage vessels are,

1) Inner vessel pressure relief valve
2) The inner shell burst disc assembly
3) The annular space burst disc assembly
4) Filling line
5) Emptying line

B. Design Data for Vertical Cryogenic Fluid Storage Vessel

Here we consider two cases for design of cryogenic storage vessel. First case consist inner vessel made up of SA-240 (S.S 304) and in second case inner vessel is made up of Aluminium (6063 T_4).

1) *CASE-I*

Liquid to be stored :Liquid nitrogen (LN2)

Capacity of the vessel : 120 liters

Ullage space : 10%

Type : Cylindrical vertical type with elliptical heads.

Design internal pressure : 20 atm (2.026 x 10^6 Pa).

Type of insulation : Perlite insulation

Type of material

Inner vessel : SA-240 (SS 304)

Outer vessel : SA-285 grade C Carbon steel

Suspension system : SA-240 SS 304

Support system : SA-285 grade C Carbon steel

2) *CASE-II*

Liquid to be stored : Liquid nitrogen (LN2)

Capacity of the vessel : 120 liters

Ullage space : 10%

Type : Cylindrical vertical type with elliptical heads.

Design internal pressure : 20 atm (2.026 x 10^6 Pa).

Type of insulation : Multilayer insulation

Type of material

Inner vessel : Aluminium (6063 T4)

Outer vessel : SA-285 grade C Carbon steel

Suspension system : SA-240 SS 304

Support system : SA-285 grade C Carbon steel

II. GENERAL DESIGN PROCEDURE OF STORAGE VESSEL

A. *Inner Vessel Design*

The product container must withstand the design internal pressure, the weight of the fluid within the vessel, and bursting. There is no beam bending in the vertical vessel. The vessel must be constructed of a material compatible with cryogenic fluid. Therefore stainless steel, aluminium, monel, and in some cases copper are commonly used for the inner shell. These materials are more expensive than ordinary carbon steel. So, the designer would like to make the inner vessel wall as thin as practical in order to hold the cost reasonable without sacrificing the strength.

$$T = (PD) / (2\ Sa\ e_w - 1.2\ P) \qquad (1.1)$$

Where, Sa = Allowable Stress,

e_w = Weld efficiency = 100%

P = design internal pressure

D= inside diameter of the shell

Do= outside diameter of the shell

The minimum thickness for the cylindrical shells, elliptical head is determined from

$$t_h = (PDK) / (2\ Sa\ e_w - 0.2\ P) \qquad (1.2)$$

B. *Outer Vessel Design*

The outer vessel is design to withstand against only collapsing or critical pressure. The outer vessel is always subjected to ambient pressure. The performance of the insulation deteriorates by the condensation of moisture. Thus outer vessel acts as a vapor barrier for the insulation. The shape of outer vessel is concentric to inner vessel and size is large than inner vessel in order to provide insulation and piping. The theoretical collapsing external pressure Pc for perfectly formed cylindrical shell is given by

$$Pc = 0.5\ E\ [t_h/Ro]^2 / [3\ (1-v)^2]^{½} \qquad (1.3)$$

Where, E= Young’s modulus of shell material

t_h= head thickness

Ro= Outer radius of shell

v= Poisson’s ratio for shell material

The collapsing or critical pressure Pc is given by the following expression according to the ASME code

Pc = 4 Pa

The factor 4 is required for safety and Pa is the allowable external pressure.

C. *Design of suspension system*

A suspension system is very important component in the figure design and construction of a storage vessel from heat transfer point of view. A poor suspension system can nullify the effect of high efficiency insulation as it account for major heat transfer next to insulation.

The suspension system should be as thin as possible and as long as possible for minimum heat in leak. The strength of material of suspension system should be high so we can get small area. And thermal conductivity should below. The efficiency of suspension system is also expressed in the ratio of its strength and thermal conductivity known, as strength to conductivity ratio should be high. In this paper stainless steel rods are used. Because, design procedure is relatively simple, fabrication is convenient, and it can withstand up to temperature lower than LN_2.

For stationary type vessel the various basic loads that the inner vessel suspension system should bear are,

1) Material weight of the inner vessel alone.
2) Weight of the inner vessel contents.

D. *Design of Piping*

It is necessary to remove cryogen from the container. For this purpose piping design for various pipes is to be carried out. While designing the pipe, it is very important to see heat-in-leak into the product container is piping. The piping runs are made as long as possible and thin walled pipe is used. Schedule 5 pipes and schedule 10 pipe is typically used in cryogenic storage vessel. The minimum wall thickness for piping subjected to internal pressure is determined according to the ASME code for pressure piping.

$$t = \frac{p * Do}{(2 * \mathrm{ft} * \mathrm{nj} + 0.8\mathrm{p})}$$

Where, P = pressure

Do = diameter of vessel

Ft = allowable stress

Nj = efficiency of weld

E. Insulation Selection

In large scale equipment heat flow must be kept very small to conserve refrigeration or to preserve liquid having small heats of vaporization. The choice of insulation for a particular application is a compromise among economy, convenience, weight, ruggedness, and volume and insulation effectiveness. The radiant heat transfer is smaller than the solid conduction heat transfer between atmospheric temperatures to LN2 temperature. But at lower temperature solid conduction dominates and hence vacuum insulation are better below LN2 temperature.

F. Boil-off Rate Calculation

Boil-off rate is calculated to judge the performance of storage vessel (insulation). It shows the effectiveness of the insulation along with its economic aspects.

$$\% \text{ boil off per day} = (Q_T / E_t) \times 100$$

Where, Q_T = total heat in leak to the vessel during one day

E_t= total heat energy required to evaporate all the quantity of liquid from the storage vessels

$$E_t = \varrho_f \times h_{fg} \times V \quad (1.5)$$

Where, ϱ_f= density of liquid

h_{fg}= latent heat of evaporation

V = volume of liquid

Now, Total heat in leak (Q_T) is made of three components, and Q_T is determined by,

$Q_T = Q_1 + Q_2 + Q_3$ (1.6)

Where, Q_1 = Heat in leak through insulation

Q_2=Heat in leak through suspension system

Q_3 = Heat in leak through piping

Method to find out heat in leak is given under

1) Heat transfer through insulation

Heat transfer through insulation is:

$Q_1 = k_{m\,x}\, A_m \times \Delta T / \Delta X$

Where, k_m = Thermal conductivity of insulation

A_m = Mean surface area of two shells

$= (A_2 - A_1) / \ln (A_2 / A_1)$

ΔT = Temperature difference $= (Ta - T_l)$

Where,Ta = Ambient temperature

T_l = Liquid temperature

ΔX= Annular space between two vessel

2) Heat transfer through top and bottom head portion of insulation

$Q_2 = k_m \times A_m \times (T_h - T_c) / L$

Where,k_m= Mean thermal conductivity of the rod

T_h= Temperature of the warm end of the rod

T_c= Temperature of the cold end of the rod

Am = Cross- sectional area of the rod

= (A1*A2)^(1/2)

L= Length of the rod

3) Heat transfer through the suspension system

Heat transfer through the suspension system is determined from the Fourier rate equation considering the effect of variable thermal conductivity:

$Q_3 = k_m \times A_m \times (T_h - T_c) / L$

Where,k_m= Mean thermal conductivity of the rod

T_h= Temperature of the warm end of the rod

T_c= Temperature of the cold end of the rod

Am = Cross- sectional area of the rod

L= Length of the rod

4) Heat transfer through piping

Heat transfer through piping is also determined from the Fourier rate equation considering the effect of variable thermal conductivity.

$Q_4 = k_m \times A_m \times (T_h - T_c) / L$

Where, k_m= Mean thermal conductivity of the pipe

$= (k_h - k_c) / (T_h - T_c)$

T_h= Temperature of the warm end of the pipe

T_c= Temperature of the cold end of the pipe

A= Cross- sectional area of the pipe

L= Length of the pipe

III. RESULT COMPARISONS FOR CASE-I &CASE-II

In this paper we select two materials as inner vessel and different insulation as discussed above. By using same design methodology as discussed in paper we designed two tanks as per design criteria given earlier in this paper and also compare that results for both case and give suggestion for suitable design from above two. As shown in table for case II thickness of inner vessel is more than case I so weight of vessel increases as thickness increases. But on the same side the other parameters are approximately same for both the cases.

Parameter	CASE I	CASE II
Thickness of Inner vessel	5 mm	14mm
Thickness of outer vessel	5 mm	14mm
Total weight of vessel	2.90 kN	4.00 kN
Heat transfer rate	7.26 W	7.37 W
Boil off rate	3.25%	3.3%

Table. 1: Analytical Data

IV. CONCLUSION

From above study we can see that the thickness for case-ii is more than case-I. Also there is a difference in weight for both cases. But the value of heat transfer rate is 7.26 W for case-I and 7.37 W for case-ii which is approximately nearer to each other so we can conclude that the heat transfer rate for SS-304 as inner vessel is same for the Aluminium alloy as inner vessel. Same way the boil off rate is 3.25% and 3.3% respectively for the both cases. From above analytical study we conclude that, we can also use aluminium alloy as inner vessel for cryogenic fluid storage vessel. We also planned to do some experimental work for the above study and give some better conclusion which is helpful to other researcher.

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