Design of Vacuum Insulated Transferable Cryogenic Vessel

Abstract: Technical gases becomes liquid in extremely low temperature ranging - 200 °C and very high pressure what makes that transportation devices have to perform very strict requirement. Cryogenic vessel is simply saying insulated pressure vessel which is used to store cryogenic liquid at cryogenic temperature which is – 162 °C. Presented paper shows designing aspect of the transportable cryogenic vessel for storing and transporting the cryogenic liquids like LNG for Indian rail road conditions.

Mobile vessel which is the object of design is a two shell tank with vacuum and layer insulation between shells container. It is assigned for see, railway and road transport and have to follow all of requirements for such transportation systems. Requirements for such tank are enclosed in standard ISO 1496-3 which deals with freight containers and standard EN13530-2 that describes vacuum, cryogenic vessels.

Vessel will designed for the truck which is commonly used in industries & known as dumper. So that vessel can be transported easily on this truck from one place to another place. No special vessel truck is required for transportation. Objective of this paper design cryogenic vessel which is minimize the gap between the stationary and transportable cryogenic vessel by designing vessel which can full fill both the requirement.

I. INTRODUCTION

The denotation “cryogenics” is defined as the study of a liquefied gas at very low temperature (below −150°C), as well as how materials perform at the aforementioned temperature. At cryogenic temperature all gases are in liquefied form. For example at -162 c temp. Methane is in liquefied form and it has 580 times less volume then it is at room temperature. So it is possible to transport large quantity of methane in small tank.

The cryogenic fluid is methane, which presents very good flammable qualities allowing it to be used as a new fuel and energy source. It is used in numbers of industries as fuel in boilers or in chemical industries

Methane can be transported in liquid state at cryogenic temp. in cryogenic vessel or in compressed for pressure above 350 bar in convectional pressure vessel[3]. But it is more economical to transfer methane at cryogenic temperature Then in compressed [1], [9].

Cryogenic vessels could be transportable (by road, by train or by boat) or stationary (set on a gas plant, for instance).

At current scenario size of Industries are becoming smaller. Medium sized and contract base industries are developing very rapidly. This kind of industries requires medium sized cryogenic tank which can transport 1000 to 4000 liters of cryogenic liquids. Current requirement of industries is a tank which can transport required quantity of cryogenic liquids and which can be also works dually as transportable or stationary storage.

So this paper prescribe design a vacuum insulated cryogenic vessel with different supportive component. This vessel is designed according to cryogenic standard like ISO 1496-3 & EN13530. Mathemetic calculation is carried out for forces and thickness of different parameters according to standards. Modeling is carried out on software pro-e.

II. TRUCK

It is necessary to find a truck which fulfils the requirements regarding dimensions, Maximum payload and the possibility of attaching a hook-lift mechanism onto it, to load and unload the vessel on the truck chassis.

The chosen truck is the TATA 4x2 Truck, which belongs to the TATA FM13 range [4]. Its main dimensions are shown in figure 1 and some other specifications of the truck are listed below.

![Figure 1 Dimensions of the TATA 4x2 Truck](image)

Chassis dimensions:
- Wheelbase (WB): 3600 mm
- Overall chassis length (A): 7137 mm
• Centre of rear axle to back of cab (D): 2604 mm
• Theoretical wheelbase (T): 4285 mm

Plated weights:
• Gross vehicle weight: 34000 kg
• Gross combination weight: 44000 kg
• Maximum payload: 10000 kg

III. THEORETICAL CALCULATION:

A. Design of Inner vessel:
Requirements for such tank are enclosed in standard ISO 1496-3 which deals with freight containers and standard EN13530-2 that describes vacuum in cryogenic vessels.

The standards EN13530-2 defines that vessels which are to be filled equal or less than 80% should be fitted with surge plates to provide vessel stability and limit dynamic loads. Additionally surge plates area has to be at least 70% of cross section of the vessel and volume between surge plates shall be not higher than 7.5m³. Structure of the vessel as well as the surge plate should resist of longitudinal acceleration of 2g.

For given configuration of truck and frame the best size occupied on it is length 3000 mm, width 1800 mm and height of 1100 mm (data available from pressure vessel design).

For stress calculation for this dimension is done on base of Clavarino’s equation according to used for the pressure vessel.[5]

\[ t = r \left[ \frac{\sigma_t + \left(1 - 2\mu\right)P}{\sigma_t - \left(1 + \mu\right)P - 1} \right] \]

\[ \sigma_t = \text{tensile stress N/mm}^2 \]
\[ \mu = \text{Poisson’s ratio} = 0.3 \]
\[ P = \text{design pressure} \]
\[ \sigma_y = \text{yield stress} = 0.8\sigma_t \]
\[ r = \text{radius of the vessel (minor axis radius in case of the elliptical vessel)} \]

B. Design pressure calculation:
Three pressures is require for the calculation of design pressure. This pressure can be calculated based on Swedish standard SS-EN 13530, Part 2.

Notation:
\[ P_t = \text{Test pressure} \]
\[ P_s = \text{Maximum allowable pressure} \]
\[ P_c = \text{Pressure during operation} \]
\[ P_l = \text{Pressure exerted by the mass of the liquid contents when the vessel is filled to capacity 1 litter} \]
\[ P = \text{Internal design pressure (this pressure is used for designing cryogenic vessel)} \]

The maximum allowable pressure in case of natural gas is 1 bar but we will take 4 bar. For calculating \( P_l \) required mass of the liquid when filled up to L level for our problem is 0.14 bar (available from standard catalogue).

Now \( P_t \) is calculated based on bellowed equation

\[ P_t \geq 1.3(P_s + 1.5 \text{ bar}) = \]
\[ P_c = P_s + P_l + 1.5 \text{ bar} = \]

The 1.5 bar added in both equations comes from the effect of the vacuum. Since vacuum has no pressure, it is necessary to add an extra pressure of 1.5 bar acting on the outer surface of the inner vessel in the opposite direction of the atmospheric pressure direction in order to equilibrate the gradient of pressures between the vacuum and the inside of the inner vessel. This extra pressure, in turn, comes into the inner vessel following the same direction as the other pressures (test pressure and pressure during operation).

According to the Swedish standard SS-EN 13530, Part 2, the internal design pressure shall be the greater of \( P_t \)and \( P_c \)corrected for operating conditions \( K_{20}/K_t \) to take into account the cold properties of the used material. In this case, as \( P_t > P_c \), the final internal design pressure \( P \) is:

\[ K_{20} = \text{the yield strength at room temperature} = 290 \text{ MPa} \]
\[ K_c = \text{yield strength at cryogenic temperature} = 386 \text{ MPa}, \text{at a temperature of} -196^\circ \text{C} \]

\[ P = P_t K_{20} / K_t \]

From below equation the value of the thickness of the vessel can be obtained.

\[ t = r \left[ \frac{\sigma_t + \left(1 - 2\mu\right)P}{\sigma_t - \left(1 + \mu\right)P - 1} \right] = 4.1 \text{ mm} \]

which is less than its 1/10 of its diameter.

So that this cylinder is taken as thin vessel with t(4.1)<<<<D(450) so we can take designing problem as shell problem.

Now so maximum stress calculation can be done on formula \( \sigma_t = Pd / 4t \)

C. Design of end plat of the vessel:
Consider the unstayed flat plate with uniformly distributed load :

\[ t_1 = d \left( \frac{kp}{\sigma} \right)^{1/2} \]

For integral flat plate K = 0.162

D. Outer jacket Design
The outer jacket is intended to hold the inner vessel and the vacuum insulation system. It presents the same shape as the inner vessel; therefore its characteristics are similar.

The chosen material for this part is the AISI 1040 carbon steel. It is selected because it has high yield strength (353 MPa), which is translated for a smaller thickness than if a weaker material were used.

Inner and outer vessel is connected by beams so that total weight is transferred from inner vessel to
outer vessel throw this beams. So localized stress induced in the outer jacket is given by bellowed equation.

$$\sigma_t = \frac{k \cdot m \cdot g}{\pi \cdot (d_o^2 - d_i^2)} \cdot \sigma_p$$

Where $k =$ constant whose value is depends upon the orientation of the beam and vessel for example is beam is perfectly in horizontal way then the $k =$ number of beam carrying full load + number of beam carrying partial load

Where $\nabla$ is fraction of load shared by the beam
So for particular analysis the yield strength of outer jacket is required must be $> \sigma_t$

$\sigma_p =$ stress due to vacuum between inner vessel and outer vessel. Vacuum pressure mostly taken as 1.5 bars

E. Thickness of outer beam

Thickness is mostly taken as 1.5t to 2.5t because it is exposed in the outside so that it required higher thickness then inner vessel.

F. Surge plate;

In the internal part of this vessel there are five surge plates that reduce the effect of moving waves of liquid while the truck accelerates. The study of surge plate is carried out by E. Lisowski[3]. The design of surge plate and its effect on wave propagation is carried out by him.

During designing of surge plate some rule is required to follow according to the ISO Standard and EN 13458-2 (2002), sated bellow

1) Surge plate follows same shape as vessel but it is horizontal at top and bottom because at bottom to make possible to fill the vessel from one position and at top part for letting gases flow through it.

2) The surge plates cover an area of approximately 70 % of the cross-section area of the inner vessel, according to the Swedish standard SS-EN 13530, Part 2.

The force applied on surge plate is 2g. So the design is done on basis of it. Force is assumed to uniformly distribute through the plate.

G. Beam Design:

The beams are intended to join the inner vessel and the outer jacket, in other words, to keep them attached. As a result, they transmit the forces from one to the other. The distribution around the vessels. Beams can be classified in two groups: firstly, the group formed by the beams which are on the top and on the bottom of the inner vessel; and secondly, those which are on the sides of it. Regarding the first group, the total number of beams is 16, distributed symmetrically in four different rows: two of them on the top of the inner vessel and the other two on the bottom of it.

The design criteria for the beam are stated bellow:

$$\sigma_t = \frac{p \cdot d}{4t}$$

$d =$ is mean diameter of the beam

Here buckling stress is avoided because length of beam is much smaller then diameter of beam. Thickness of beam obtained by maximum force that can be transferred by beam. It is the weight of vessel distributed over the different section of beam. It depends upon the location of the beam between inner and outer vessel so for this different analysis is carried out for different location of beam and tried to find out best arrangement of different beam.

IV. 3D MODELING

Certain hypothesis is formulated to carry out design procedure.

- All parts are modelled as surface models in order to idealize them with shell elements in the finite element analysis.
- All pipes and all connections between the inner vessel and the outer jacket are idealized as beams with a specified cross-section for each one of them.
- Since all mechanical analyses are made for the whole unit, it is necessary to set constraints in one of the parts. As the frame is the part in contact with the truck, the frame is the one that has the constraints. These constraints are located in one place or another depending on the position of the assembly.
- In finite element analysis, considerations such as “numerical singularities” (they come up in the meeting point of several sharp edges or corners) and “incompatibilities” (locations with large concentration of stresses that come from the union or connection of the beam idealization with the shell idealization) are taken into account, but they are ignored due to the fact that they are not physically real. Regarding incompatibilities, the finite element module does not take into account the whole section of the beam, rather only taking into consideration one single point. Thus, the same stress values are obtained by using different beam cross-section values within the same conditions (loads and constraints).
- The mechanical analysis of the complete assembly is performed with three different loads. These loads are the gravity (9.81 m/s²), an incoming pressure load of 2 bar affecting the outer surface of the outer jacket and an outgoing pressure load of 5 bar affecting the inner surface of the inner vessel.
In each part, the value of the safety factor, which comes from the ratio between the yield strength and the maximum stress value, is given. The tensile strength is not considered for this calculation as criteria for failure.

The union of each part with another is supposed to be obtained through welding processes, which are considered as multi-point constraints. These constraints set the nodes of a surface to have the same displacement as the nodes of another surface. Thus, the final assembly is considered as one unit.

A. Inner Vessel Design:
3D model of the inner vessel is shown in fig. 1 with detailed drawing in appendix

B. Surge plate:
In the internal part of this vessel there are five surge plates that reduce the effect of moving waves of liquid while the truck accelerates. They have a thickness of two millimeters and they are placed with a distance between them of 550 mm.

The shape of the surge plates follows the shape of the vessel but ends with horizontal edges at the top and bottom part.

C. Beams:
The beams are intended to join the inner vessel and the outer jacket, in other words, to keep them attached. As a result, they transmit the forces from one to the other. The distribution around the vessels.

Position of the initially beam is shown in fig. Beams can be classified in two groups: firstly, the group formed by the beams which are on the top and on the bottom of the inner vessel; and secondly, those which are on the sides of it. Regarding the first group, the total number of beams is 16, distributed symmetrically in four different rows: two of them on the top of the inner vessel and the other two on the bottom of it. The distance between each beam is 664 mm and each one has an angle of inclination of 45° from the horizontal symmetry plane of the inner vessel (front plane). Regarding the second group, the total number of beams is 8, four on each side. They are placed symmetrically around each surface and they are perpendicular to the surfaces of the inner vessel and the outer jacket.
REFERENCE


