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Design and Analysis of a Large Transportable Multilayer Composite Vacuum Insulated Cryogenic Vessel

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ABSTRACT

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. In this case, the cryogenic fluid is methane, which presents very good flammable qualities allowing it to be used as a new fuel and energy source

This project is deals with design and analyzes a large transportable vacuum insulated cryogenic vessel that will be attached to a truck in order to keep, maintain and transport by road liquid methane. To get more efficient object here we also consider one more design with two layers and analyzes with composite materials, finally we give comparison between cryogenic vessel and multi layer cryogenic vessel with static and thermal loading conditions.

Considerations such as different pressure loads, dimensions, materials as well as their mechanical properties, constraints, masses, insulation systems and weather-environmental conditions are made in the mechanical analysis. The CAD software Pro/Engineer (creo-2) is used to visualize the models for the chosen designs. In addition, the finite element module ANSYS WORKBENCH 15.0 is used to obtain results of mechanical analyses in order to determine if the stresses are within margins.

Finally this project concludes which is most suitable material at different loading conditions.

Tools were used:

- **Cad tool: creo-2**
- **Cae tool: Ansys workbench 15**

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. In this case, the cryogenic fluid is methane, which presents very good flammable qualities allowing it to be used as a new fuel and energy source. By being liquefied, methane reduces its volume approximately 580 times at room pressure (1 bar), which makes it possible to transport a large quantity of methane in a small tank, which can be transported by a truck.

Cryogenic vessels could be transportable (by road, by train or by boat) or stationary (set on a gas plant, for instance). Moreover, vessels could be insulated by vacuum or by special insulation material (foam, for example).

This project is aimed at the design and analysis of a transportable cryogenic vessel composed of several parts. Methane is kept in an inner vessel covered by an outer jacket of the same shape. Between both vessels, a vacuum insulation system is located. There are also beams which are used as connections between the inner vessel and the outer jacket and these are designed, analyzed and optimized in order to obtain stress values within margins. Apart from this, the project also addresses the frame to which vessels are attached, as well as its supports, which are the connections between the vessels and the frame. Finally, pipes and valves are taken into consideration in order to complete the design of the cryogenic vessel.

This project is structured around two parts. The first part contains a background on methane, the truck with the hook-lift mechanism and the insulation system. The second part focuses on the design and finite element analysis of the cryogenic vessel assembly.

2. BACKGROUND INFORMATION

The vessel is intended to carry methane. Therefore, in order to gain a better knowledge of this element, some characteristics are mentioned bellow. Since the properties of methane affect the design and analysis of the vessel, a truck with a hook-lift mechanism is intended to transport the vessel and thus an overview of them is studied.

Vacuum is selected as the insulation system. There are various kinds of methods for vacuum insulation. The description of these appears below.

2.1. Methane

Methane is a chemical compound with the chemical formula CH4. It is the principal component of natural gas (about 87 % by volume). The relative abundance of methane makes it an attractive fuel. However, given that methane is a gas at normal temperature and pressure, it is difficult to transport. Methane in a gas state is flammable only when its concentration in air fluctuates between 5 and 15 %. Liquid methane does not burn unless subjected to a high pressure of 4 – 5 atmospheres normally.

Regarding potential health hazards, methane is not toxic. However, it is highly flammable and may form explosive mixtures on contact with air. It is violently reactive with oxidizers, halogens and some halogen-containing compounds. It is also suffocating and it may displace oxygen in an enclosed space. A decrease in its oxygen concentration down to or below 19.5 % by displacement may result in asphyxia.

Methane is important for the generation of electricity by burning it as a fuel in a gas turbine or steam boiler. Compared to other hydrocarbon fuels, burning methane produces less carbon dioxide for each unit of released heat. With 891 kJ/mol, methane's heat of combustion is lower than any other hydrocarbon, but the ratio of the heat of combustion regarding the molecular mass (16 g/mol) shows that methane, being the simplest hydrocarbon, produces more heat per mass unit (55.7 kJ/g) than other hydrocarbons. In many cities, methane is distributed into homes for domestic heating and cooking purposes. In this context it is usually known as natural gas and it is considered to have an energy content of 39 MJ/m3 at a temperature of 0 ºC and a pressure of 1 bar.

Methane in the form of compressed natural gas is used as a vehicle fuel and it is claimed to be more environmentally friendly than other fossil fuels such as gasoline/petrol and diesel.

Methane is often kept in the transportable vessel in a liquid state (denoted “liquefied methane gas”, LMG), given that it is possible to keep more liquefied methane than gas methane within the same volume space, as the ratio of volumes is 1/580. Methane is in a liquid state at a temperature of -160 ºC and a pressure of 1 bar. It has a density of 415 kg/m3. Methane is also less dangerous in a liquid state regarding fire and explosions matters.

2.2. Truck and hook-lift mechanism

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 Volvo 6x4 T Ride Tractor, which belongs to the Volvo FM13 range. Its main dimensions are shown in figure 1 and some other specifications of the truck are listed below.
Figure 1. Dimensions of the Volvo 6x4 T Ride Tractor given in millimetres.

Chassis dimensions:
Wheelbase (WB): 3600 mm
Overall chassis length (A): 7137 mm
Centre of rear axle to back of cab (D): 2604 mm

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Theoretical wheelbase (T): 4285 mm

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

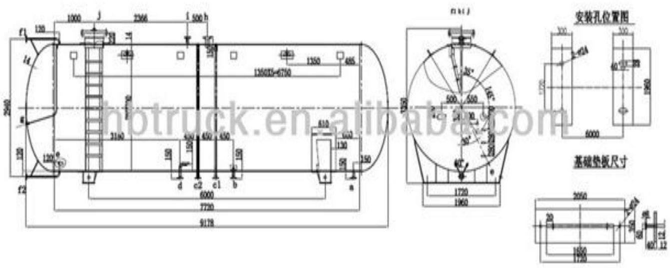
The hook-lift system is a mechanism used to load and unload containers by using a hook. There are many companies specialized in manufacturing different hook-lift systems depending on the model of the truck.

A vacuum insulation system that fulfils specific mechanical requirements is needed. MLI is generally very sensitive to mechanical compression and edge effects. Since the vessel is loaded and unloaded from a truck, it is exposed to movements that would cause critical stresses on the unit when using MLI. These stresses could affect the multi-layer insulation system, breaking its internal bonds between layers that might cause its insulation properties to decrease. For this reason, and also due to the high quality of vacuum that MLI requires, this insulation method is rejected for the vessel that is being designed. Thus, the best insulation system for this project is the perlite insulation.

3. DESIGN AND ANALYSES OF THE PARTS OF THE CRYOGENIC VESSEL

This chapter focuses on the study of the parts of which the cryogenic vessel assembly is composed. Firstly, the frame that the cryogenic vessel is standing on is analyzed. Secondly the main vessel which is composed of an inner vessel, wherein the cryogenic fluid is kept, an outer jacket (in charge of covering the inner vessel), four supports (attachment between the vessels and the frame), twenty four beams (in charge of separating the inner vessel and the outer jacket), and finally three pipes for letting some flows of gas or air going in and out of the vessels. A third main part deals with other elements that complete the whole assembly. These are the cabinet (located on one side of the frame), the valves and the vacuum gate. In figure 3, the assembly is shown, although some of the parts such as the inner vessel, the pipes, the valves and the beams are not visualized as the bottom surfaces of the frame rails. Therefore, higher stress locations are obtained.

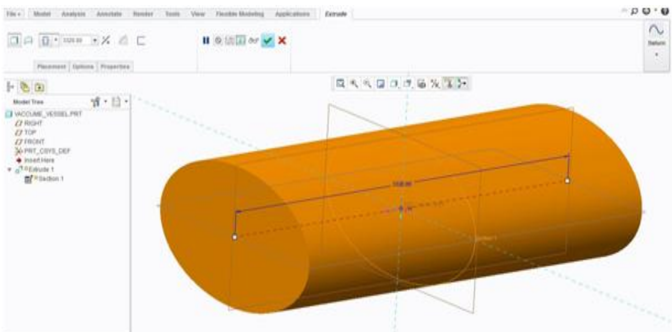
In each part, the value of the safety factor, which comes from the ratio between the yield strength and the maximum stress value, is given. The tensile strength is not considered for this calculation as criteria for failure, because the finite element module only considers the lineal behaviour of materials. Therefore, it is assumed that if the model stands the stresses and loads with the yield strength as criteria, it stands them with the tensile strength, since the yield strength is lower than the tensile strength. Below, the properties of the chosen materials are shown in Table 1.



Reference model

The main function of the inner vessel is to keep the methane at a temperature of -162ºC. Figure 8 shows an overall view, where it is possible to observe the symmetric shape of the inner vessel. It has three symmetry planes. The main dimensions are a length of 3320 mm, a width of 1900 mm and a height of 1100 mm. In order to see all the dimensions

Then-→ok→enter extrude length



for shell select vessel enter thickness

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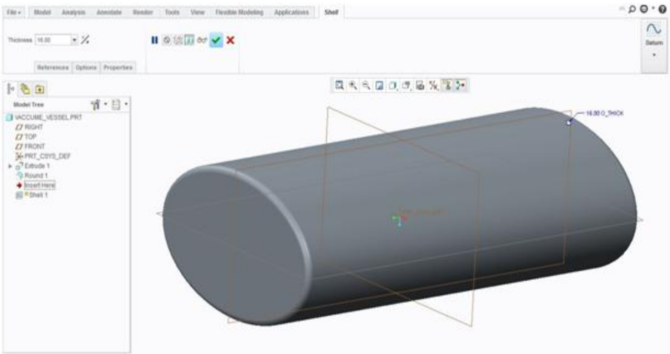
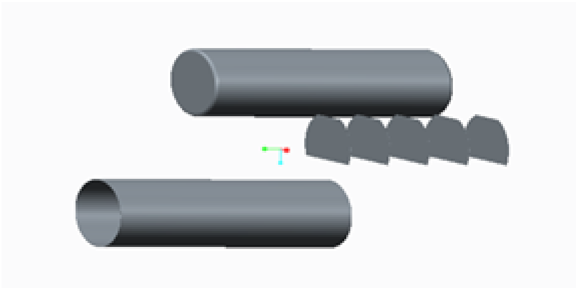


Above Figure shows two rounds in the edges. The purpose of these features is that the rounds reduce the stress concentrations where the inner vessel has sharp corners

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 (see further figure). Due to visualization errors in figure 9, it appears that some surfaces are broken. This is, however, not the case. The shape of the surge plates follows the shape of the vessel but ends with horizontal edges at the top and bottom part (see below figure). The purpose of the horizontal end at the bottom part is to still make it possible to fill the vessel from one position. The space between the horizontal edge at the top part of the surge plate and the inner vessel is an opening whose function is to let gases flow through. Thus, the pressure has the same value at all positions in the inner vessel. The distance from the top edge to the horizontal edge of the surge plate is 700 mm. The surge plates cover an area of approximately 70 % of the cross-section area of the inner vessel,

MODIFIED DESIGN

The original model was changed here; we consider here 2 different layers pressure vessel which is having outer & inner layers. Here we took outer layer and inner layer with 2:3 ratio i.e. original model has total 16mm thickness and we divided it in to 5parts and considering outer side is 2parts and inner layer with 3parts. Remaining dimensions we took as it is and followed same procedure for this model also.



Modified Design Explode View

STRUCTURAL ANALYSIS:- FOR

Stainless-steel

Ex: - 193*10^9 Pa
Poison ratio: 0.3
Density: 8030 Kg/m^3
Yield strength: 290 Mpa

CARBON-STEEL AISI 1040

Ex: 200*10^9 Pa
Poison ratio: 0.3
Density: 7845 kg/m^3
Yield strength: 353.4 Mpa

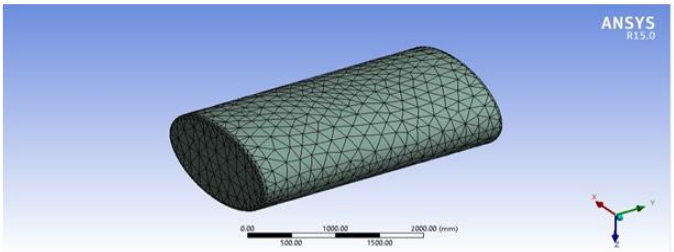
Monel_400

Ex: 125*10^9 Pa
Poison ratio: 0.32
Density: 8800 kg/m^3
Yield strength: 400 Mpa

Al-2024:

Ex: 73.1*10^9 Pa
Poison ratio: 0.33
Density: 2782 kg/m^3
Yield strength: 324 Mpa

Meshing: - Volume Mesh - Tetmesh.



Tet Volume Mesh.

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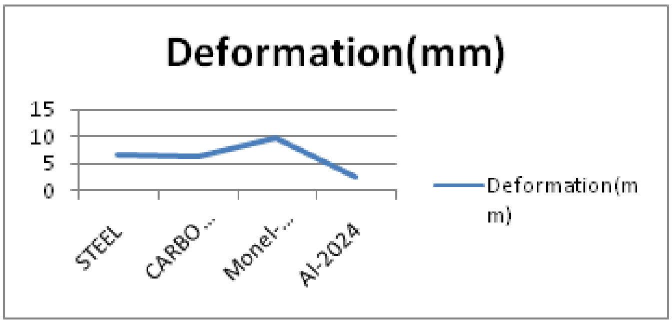
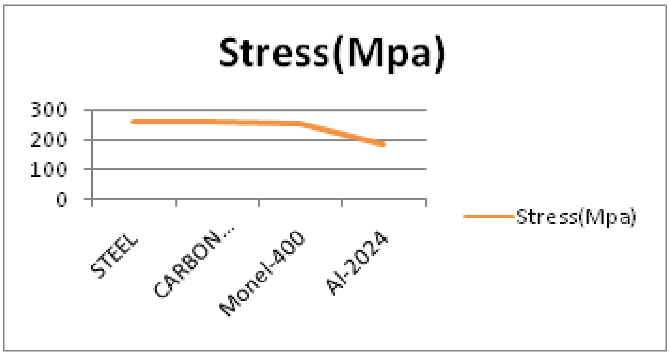
Tables

	STEEL	CARBON STEEL AISI-400	Monel-400	Al-2024
Deformation(mm)	6.45	6.2255	9.7405	2.4413
Stress(Mpa)	259.67	259.67	254.05	182.12
Safety factor	1.1168	1.361	1.5745	1.7845

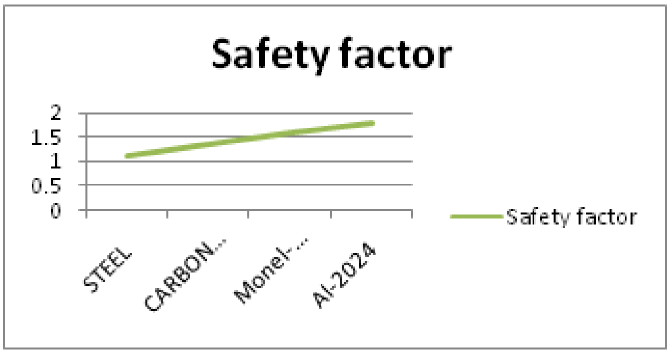
Deformation



Stress



Safety factor



COMPARISON BETWEEN ANALYTICAL METHOD AND NUMERICAL METHOD

The hydrostatic pressure causes stresses in three dimensions.

1. Longitudinal stress (axial) σL
2. Radial stress σr
3. Hoop stress σh

all are normal stresses.

a, The longitudinal stress σL

(pie D^2/4) = pie *D*t*σ**L**

if P > 0, then

$\sigma L = PD/4t$

b. The hoop stress σh

D L P = 2 L σ**h** t

$\sigma h = PD/2t$

c. Radial stress

σr $\sigma l \approx o$ (P)

varies from P on inner surface to 0 on the outer face

$\sigma h , \sigma L \approx P (D/2 t)$.

so $\sigma h , \sigma L >> \sigma r$

so neglect σr

From the model

UD = difference in strain energy (UC =1/3[$\sigma 1 + \sigma 2 + \sigma 3$]

UD =1/2E(($\sigma 1$^ 2 + $\sigma 2$^2 + $\sigma 3$^2 + 2υ ($\sigma 1 \sigma 2 + \sigma 2 \sigma 3 + \sigma 3 \sigma 1$) -1/2E[3C^2 + 6υC^2]))

And we have our dimensions here

(D = 0.19 m, t' = 0.001 m) is subject to an internal pressure of 10 barg.

σL = PD/4t' = 47.5 N / mm2

σh = PD/2t' =95 N / mm2

and $\sigma 3 = \sigma r \approx 0$

and now calculate von misses stress from the above values

for

Stainless-steel material

Ex: - 193*10^9 Pa

Poison ratio: 0.3

Density: 8030 Kg/m^3

Yield strength: 290 Mpa

From the above formula

½*193*1000((47.5^2+95^2+0+2*0.3(47.5*95+95*0+0*47.5)-1/2*193*1000(3*47.5^2+6*.3*47.5^2))

=219/8875-0.02

=219Mpa

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From the above value we calculated von misses stress results for steel material

And the safety factor is

Fos = Yield strength/design stress = 290/219

= 1.324

Repeat same formula for all materials

For

CARBON-STEEL AISI 1040

Ex: 200*10^9 Pa

Poison ratio: 0.3

Density: 7845 kg/m^3

Yield strength: 353.4 Mpa

From the above formula

½*200*1000((47.5^2+95^2+0+2*0.3(47.5*95+95*0+0*47.5)-1/2*200*1000(3*47.5^2+6*.3*47.5^2))

=235Mpa

From the above value, we calculated von misses stress results for steel material

And the safety factor is

Fos = Yield strength/design stress = 353.4/235

= 1.5038

Monel_400

Ex: 125*10^9 Pa

Poison ratio: 0.32

Density: 8800 kg/m^3

Yield strength: 400 Mpa

From the above formula

½*125*1000((47.5^2+95^2+0+2*0.3(47.5*95+95*0+0*47.5)-1/2*125*1000(3*47.5^2+6*.3*47.5^2))

=210Mpa

From the above value, we calculated von misses stress results for steel material

And the safety factor is

Fos = Yield strength/design stress = 400/210

= 1.95

THERMAL ANALYSIS

MATERIAL PROPERIES

Stainless-steel

Ex: - 193*10^9 Pa

Poison ratio: 0.3

Density: 8030 Kg/m^3

Yield strength: 290 Mpa

Thermal conductivity : 16.2 w/m .k

CARBON-STEEL AISI 1040

Ex: 200*10^9 Pa

Poison ratio: 0.3

Density: 7845 kg/m^3

Yield strength: 353.4 Mpa

Thermal conductivity : 54 w/m .k

Monel_400

Ex: 125*10^9 Pa

Poison ratio: 0.32

Density: 8800 kg/m^3

Yield strength: 400 Mpa

Thermal conductivity : 16.5w/m .k

Stainless steel Thermal heat flux

q=-k (t2-t1)/dx

Here we have

q= heat flux

t2=room temperature

t1= liquid temperature

dx= thickness of the object

From the above

Q=1.62e-2 w/mm-k *(32-(-162))/10mm

And here we converting our temperature into Kelvin units

Q=16.2*e-2*(305+435)/10

Q=16.2*738/1000

Q=1.19 w/mm^2

From the Ansys we got q=1.3988 w/mm^2

CARBON-STEEL AISI 1040 Thermal heat flux

q=-k (t2-t1)/dx

Here we have

q= heat flux

t2=room temperature

t1= liquid temperature

dx= thickness of the object

From the above

Q=5.4e-2 w/mm-k *(32-(-162))/10mm

And here we converting our temperature into Kelvin units

Q=5.4*e-2*(305+435)/10

Q=5.4*738/1000

Q=3.9852 w/mm^2

From the Ansys we got q=4.6605 w/mm^2

Monel_400 Thermal heat flux

q=-k (t2-t1)/dx

Here we have

q= heat flux

t2=room temperature

t1= liquid temperature

dx= thickness of the object

From the above

Q=1.65e-2 w/mm-k *(32-(-162))/10mm

And here we converting our temperature into Kelvin units

Q=1.65*e-2*(305+435)/10

Q=1.65*738/1000

Q=1.2177 w/mm^2

From the Ansys we got q=1.4247 w/mm^2

From the above calculations, here we got both analytical and numerical results for all materials

From these results, we **can say that 85% accurate** results from the ANSYS

CONCLUSION

In this project first we took one cryogenic vessel with stainless steel material, our aim in this project is reducing the internal stresses while applying real-time boundary conditions on the object to do this first we have to check our object with existing material

Designed one cryogenic vessel with inner vessel by using cad tool (pro-e/creo-2), to analys we imported it into cae tool (ansys workbench) then applied real time boundary conditions on it. We got stress 259Mpa and safety factor is 1.1, to reduce the stress and increasing the strength of the object we also checked another three materials those are carbon steel and monel-400 and al-alloy 2024, in this case carbon steel not satisfied our requirement but monel-400 and al-2024 satisfies.

Monel-400 reduced stress 259Mpa to 251Mpa and also safety factor increased from 1.1 to 1.54, but this monel-400 has more weight than existing material so that we change material monel-400 to al-2024. Here maximum stress 182Mpa and it means nearly we reduces stress values 77Mpa compare to existing material i.e. (nearly 33% of the original stress reduced.) and increases strength 1.1 to 1.8 i.e (1.6 times more than existing material.)

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