Numerical Investigation of the Thermal Performance of Different Shapes of Fiber-Glass/Talc-Epoxy Insulated Cryotanks

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Abstract
This study focuses on the thermal performance of different shapes of fibre-glass/talc-epoxy insulated cryotank with the aim of minimizing heat leakage into the stored cryogenic fluid. Numerical simulations were performed using a computational fluid dynamics software on rectangular-, cylindrical-, and spherical-shaped cryotank geometries while maintaining a constant inner shell volume. The outer shell was subjected to a temperature boundary condition of 28°C, while the inner shell volume was initially set to a temperature of -196°C, which is equivalent to the temperature of liquid nitrogen. The heat transfer from the environment to the cryogenic fluid stored within the cryotank was analysed, and the optimal insulation thickness that minimises the heat flux into the different cryotank shapes was determined. The results obtained revealed that the spherical-shaped cryotank had the best performance in minimising heat leakage with the lowest temperature of -156.1°C and optimum insulation thickness of 279 mm after 3 hours of storage within the tank. Optimising the insulation thickness was required to determine the minimum thickness required to maintain liquid nitrogen at approximately -196°C after one hour of storage. This was determined to be 240 mm, 180 mm and 160 mm for the rectangular-, cylindrical- and spherical-shaped cryotanks respectively. The findings in this study validates the importance of optimisation studies in the design of small and compact cryotanks to ensure material cost savings and optimal thermal performance.

Keywords: Cryogenics, Fibre-glass/talc-epoxy, Heat transfer, Thermal insulation, Liquid nitrogen

1.0 INTRODUCTION

Cryogens are kept in liquid form in a storage vessel and one of the earliest means for storing cryogenic fluid was with the use of a Dewar flask. The Dewar flask consists of a double-walled shell with a vacuum in between the walls as insulation. James Dewar is credited with creating the original Dewar flask, which bears his name (Wisniak, 2003).
It is important to choose the right material for cryogenic storage based on the specific requirements of the substance being stored, as well as the intended use of the storage vessel. Factors to consider include the material's strength, durability, thermal conductivity, and resistance to corrosion (Arnold et al, 2007). Seeli et al (2016) examined various materials used for the production of cryogenic tanks. By stress analysis, he concluded that Nickel copper alloy is better suited for producing cryogenic vessels rather than aluminium because nickel copper alloy is capable of withstanding high-pressure environment. The study focused mainly on the pressure build up due to low temperature difference between the cryotank and the environment. While Seeli et al (2016) was able to provide insight into the optimum material which could withstand pressure build-up in cryotank, the thermal conductivity of these materials was not investigated. Yinan et al (2018) in their study were able to propose stainless steel as a good material for the design of the inner and outer shell of cryotanks. They reported that stainless steel had been used extensively, particularly in liquid nitrogen storage and transportation. This is due to its superior nitrogen brittleness resistance, good low temperature performance, weldability, and corrosion resistance. However, there is room for improvement in the low-temperature mechanical characteristics of materials under particular environmental conditions. There has been a major comparison between aluminium alloy and stainless steel as materials for the design of cryogenic storage vessels. Although stainless steel has good cryogenic temperature performance, aluminium alloys have clear advantages over stainless steel because of lightweight, outstanding formability, welding performance, and superior corrosion resistance.

Both domestically and internationally, liquid hydrogen storage tanks for space missions have been made largely of aluminium alloys (Seeli et al, 2016).

In the design of a cryotank, the insulation thickness alongside the insulation material is usually of great importance. By inhibiting heat transmission from the surrounding environment, insulation aids in maintaining the stability of the temperature of the cryogenic vessel's contents. By slowing down the rate of heat transmission, a thicker insulation layer will produce better temperature stability (Song, 2021). Oludele and Oluleke (2012) investigated various insulation thickness requirements for double-walled spherical pressure vessels for the storage of cryogenic liquids. In their study, polyurethane foam, glass wool, sawdust, mineral wool and slag wool were the materials used for insulation in the cryotank. Finite element method was employed to predict the performance of the selected materials and FORTRAN 90 algorithm was used to solve the finite element equations. The findings from their numerical studies showed that as the thickness of the insulating layer increased, the heat flux into the stored product decreased and until it obtained a critical value after which the heat flux began to increase. Their results also showed that polyurethane was the best insulating material allowing a minimal heat flux of 31.6 W/m^2 at an insulation thickness of 0.279 m. Even though a larger insulation thickness is required to minimize the pressure rise in the cryotank, considerations for increase in insulation mass with increasing insulation thickness, should be taken into account while optimizing for insulation thickness (Joseph et al, 2017).

The use of fibre-glass/talc-epoxy, a locally produced composite material, as an insulator in tanks storing extremely cold fluids has never been investigated. A previous experimental and numerical study carried out, was focused on fibre-glass/talc-epoxy as an insulator in water heaters storing hot fluid (Adewumi et al., 2021). In this present numerical study, investigations are carried out to determine the thermal performance of fibre-glass/talc-epoxy as insulators in cryotanks used to store extremely cold fluids. The optimal insulation thickness that gives the best cryotank heat transfer performance is also determined.

2.0 METHODOLOGY

2.1 Model Description and Governing Equations

The three – dimensional physical model of the different shapes of cryotank considered in this study shown in Figure 1 was generated using the Autodesk Fusion 360 CAD software (Samar, 2018). The dimensions of each cryotank shape is shown in Table 1 and the shell material chosen for this study is carbon steel due to its high yield strength. The inner shell volume of the different cryotank shapes was kept at constant value for comparative investigation.

The fluid under consideration is liquid nitrogen, modelled as a single-phase fluid with constant Newtonian fluid properties and assumed to be at an initial temperature of -196ºC. The insulation material used for this investigative study is locally produced fibre-glass/talc-epoxy 1D 75 composite with a percentage mixture of 80% of epoxy, 15% of fiberglass, and 5% of talc (Adewumi et al, 2021). The insulation thickness and inner shell thickness for the initial models was based on the results obtained by Oludele and Oluleke (2012). The inner shell thickness used was determined based on standards regulated by American Society of Mechanical Engineers (ASME sec VIII DIV 1) (Boiler, A. S. M. E., 1998).

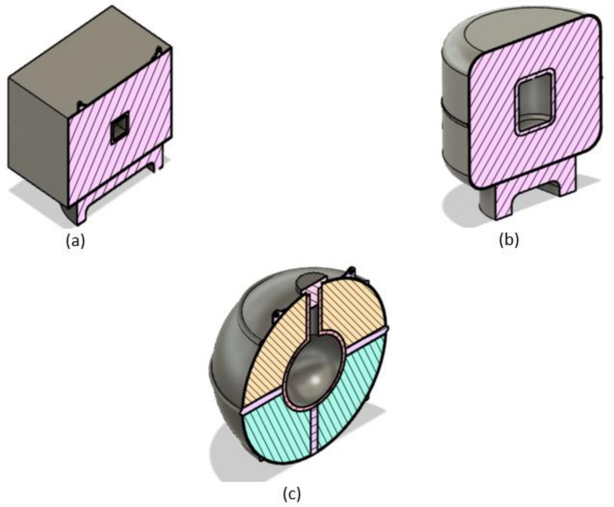

Figure 1: Physical Model of Different Shapes of Cryotanks (a) Rectangular (b) Cylindrical (c) Spherical

Table 1: Dimensions of Cryotank Shapes

	Rectangular	Cylindrical	Spherical
Inner shell thickness (m)	0.024	0.024	0.024
Insulation thickness (m)	0.279	0.279	0.279
Outer shell thickness (m)	0.06	0.06	0.06
Inner shell diameter (m)	0.20	0.20	0.20
Inner shell height (m)	0.108	0.266	-
Inner shell volume (m^3)	0.0042	0.0042	0.0042

The temperature difference between the cryogen (liquid nitrogen) and the surrounding environment causes the transfer of heat from the outer shell to the cryogen. The governing non-linear partial differential equations for fluid flow and heat transfer shown in equations (1) to (3) were solved using Autodesk CFD, a finite element analysis simulation software (Samar, 2018).

$$\frac{D\rho}{Dt} + \rho\nabla.\boldsymbol{V} = 0 \tag{1}$$

$$\rho\frac{D\rho}{Dt} = \rho g - \nabla\rho + \nabla.(\mu\nabla\boldsymbol{V}) \tag{2}$$

$$\rho C_p\left(\frac{\partial T}{\partial t} + \boldsymbol{u}.\nabla T\right) + \nabla.(-\mathrm{k}\nabla\mathrm{T}) = Q \tag{3}$$

The computational domain was discretised using a combination of hexagonal/wedge, tetrahedral, and spherical elements while the second-order upwind scheme was employed.

2.2 Grid Refinement Test

A grid refinement test was conducted to determine the suitable mesh size for the numerical simulations. The results of the grid refinement tests for the rectangular-, cylindrical- and spherical-shaped cryotanks are presented in Tables 2, 3 and 4 respectively. The minimum temperature of the cryogen in the inner shell of the cryotank was monitored for 180 minutes and the convergence criterion for the grid independence is shown in equation (4).

$$\gamma = \frac{|(\Delta \boldsymbol{T})_{i+1} - (\Delta \boldsymbol{T})_i|}{(\Delta \boldsymbol{T})_i} \leq 0.01 \quad (4)$$

Where i and $i + 1$ are the mesh indices for current and next iterations, respectively. The number of elements selected were 696816, 556724 and 419990 for the rectangular-, cylindrical- and spherical-shaped computational domains respectively.

Table 2: Grid Refinement Test for Rectangular-Shaped Cryotank

No. of elements	Minimum temperature (°C)	$\frac{\|(\Delta \boldsymbol{T})_{i+1} - (\Delta \boldsymbol{T})_i\|}{(\Delta \boldsymbol{T})_i}$
177032	-132.64	0.025
350845	-135.9	0.024
696816	-139.2	0.004
1308942	-139.7	0.003

Table 3: Grid Refinement Test for Cylindrical-Shaped Cryotank

No. of elements	Minimum temperature (°C)	$\frac{\|(\Delta \boldsymbol{T})_{i+1} - (\Delta \boldsymbol{T})_i\|}{(\Delta \boldsymbol{T})_i}$
123783	-139.5	0.067
262943	-148.9	0.014
556724	-150.99	0.001
1128420	-151.2	0.001

Table 4: Grid Refinement Test for Spherical-Shaped Cryotank

No. of elements	Minimum temperature (°C)	$\frac{\|(\Delta \boldsymbol{T})_{i+1} - (\Delta \boldsymbol{T})_i\|}{(\Delta \boldsymbol{T})_i}$
98904	-143.5	0.051
203989	-150.9	0.034
419990	-156.18	0.001
804832	-156.4	0.001

2.3 Validation of CFD Codes

The heat transfer experiment shown in Figure 2 carried out by Ortuno et al. (2011) was modeled and simulated using Autodesk CFD software. The numerical results obtained were compared with the experimental results previously obtained. Table 5 shows that the minimum and maximum temperature numerical results by 3.2% and 0.9% when compared with the experimental results.

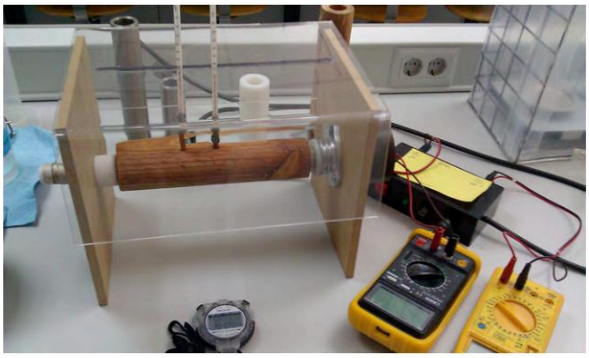

Figure 2: Experimental Determination of the Thermal Conductivity of a Cylindrical Polyethylene Material (Ortuno et al, 2011)

Table 5: Numerical Validation Results

	Max. Temperature (℃)	Min. Temperature (℃)
Numerical	85.8	45.46
Experimental	85	47

2.4 Determination of Optimal Insulation Thickness

Determining the critical insulation thickness involves identifying the numerical value where further increase in insulation thickness has negligible effect on the minimizing heat leakage. This range represents a balance between the thermal performance requirements and practical considerations, such as cost, weight, and space limitations. From literature, the storage time for 1 to 5 litres of cryogenic product was within the range of 10 to 50 minutes before boiling starts. Therefore, the optimization process was carried out for a storage time of 60 minutes to determine the minimum thickness to maintain nitrogen at -196°C*.* The insulation thickness was increased from 10 mm to 1000 mm in steps of 20 mm while monitoring the fluid temperature within the inner vessel of the cryotank.

2.5 Determination of Thermal Stress on Inner and Outer Shell Material

The structural integrity of the spherical-shaped aluminium cryotank with fibre-glass/talc-epoxy insulation was numerically investigated in this study using Autodesk Fusion 360 thermal stress simulation tool. Stresses on the cryotank material due to the extreme cryogenic temperature of -196°C on the inner shell and $28°\ C$ on the outer shell were obtained to determine the structural integrity of the cryotank.

3.0 RESULTS AND DISCUSSION

3.1. Results of Temperature and Heat Flux

The transient-state simulation of temperature and heat flux was carried out with a time step of 10,800 seconds and an initial temperature of -196°C on the cryogenic product. Table 6 shows the results of heat leakage and minimum temperature of the fluid for each shape of cryotank for a constant insulation thickness of 279 mm.

Table 6: Results of Temperature and Heat Leakage into the Cryotank

Shape	Heat leakage (Watts)	Total surface area (cm^2)	Minimum temperature (°C)
Rectangular	136.5	76116.8	-139.2
Cylindrical	63.9	57376.8	-150.9
Spherical	49.8	45226.4	-156.1

The rectangular-shaped cryotank had the highest heat leakage of 136.5W into the inner vessel holding the cryogenic product followed by the cylindrical shape with 63.9 W. The spherical-shaped cryotank displayed the lowest heat leakage of 49.8 W which has a direct influence on the minimum temperature of the cryogenic fluid.
Though a constant volume constraint was applied for all the cryotank shapes, surface area played a crucial role in heat leakage into the inner shell of the cryotank. This is consistent with the theory of heat transfer where a larger surface area gives a higher rate of heat transfer (Rajput, 2015). The rectangular-shaped cryotank had the largest surface area of 76,116.8 cm^2, followed by the cylindrical shape with 57,376.8 cm^2 and then the spherical shape with the smallest surface area of 45,226.4 cm^2. The temperature variation with time across the cryotank for each shape is presented in Figure 3, which shows that spherical-shaped cryotank maintained the lowest cryogenic fluid temperature through the simulation time of 180 minutes.

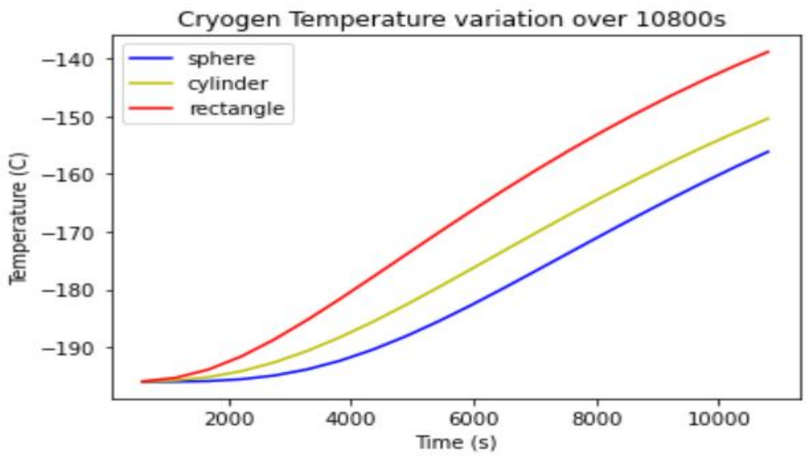

Figure 3: Cryogenic Fluid Temperature Variation with Time

3.2 Results of Optimal Insulation Thickness

Figure 4 shows the effect of increasing insulation thickness on the cryogenic fluid temperature stored in the different shapes of cryotank.

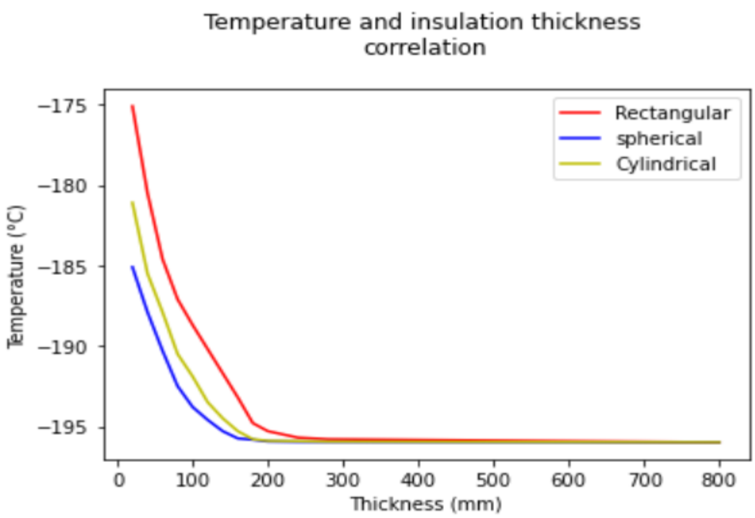

Figure 4: Effect of Insulation Thickness on Cryogenic Temperature

Comparing the optimal insulation obtained numerically for the different cryotank shapes considered in this study, the following observations were made;

(i) A 279 mm insulation thickness for the rectangular-shaped cryotank gave a minimum cryogenic temperature of -195.8℃ before optimization was carried out. After optimization, an optimal insulation thickness of 240 mm resulted in the same cryogenic temperature of -195.7℃ i.e., optimising the insulation thickness resulted in the reduction of insulation thickness by 13.9% while maintaining the cryogenic temperature of approximately -196℃.

(ii) For the cylindrical-shaped cryotank, a 279 mm insulation thickness maintained the cryogenic temperature of the fluid at -195.95℃ while an insulation thickness of 180 mm was obtained after numerical optimization with cryogenic fluid temperature of -195.8℃. This also shows that the numerical optimization process reduced the required insulation thickness by 35.5% while maintaining the temperature of the stored liquid nitrogen at approximately -196℃ for 1 hour.

(iii) A similar trend is observed for the spherical-shaped cryotank where the initial 279 mm insulation thickness resulted in a cryogenic temperature of – 195.95 ℃ while an insulation thickness 160 mm maintained a cryogenic temperature of – 195.75℃ i.e., a 42.7% decrease in insulation thickness was achieved due to numerical optimization while maintaining the cryogenic temperature at approximately -196℃ for 1 hour.
The optimized dimensions for insulation thickness across the three cryotank models represent a balance between the thermal performance requirements and practical considerations, such as cost, weight, and space limitations.

3.3 Determination of Optimal Shell Material

This section presents results from the numerical investigation to determine the best material to be selected for the fabrication of the inner and outer shell of the spherical-shaped cryotank with optimal insulation thickness. The three materials selected for this study were stainless steel, aluminium and carbon steel. The data presented in the Table 7 shows the minimum cryogenic temperature for each of the material after three hours of storage with insulation thickness of 160 mm. Table 7 shows that when aluminum material is used as the inner and outer shell material with fibre glass/talc-epoxy composite used as the insulation material, the lowest cryogenic temperature is achieved.

Table 7: Effect of Cryotank Material on Cryogenic Temperature

Material	Minimum Temperature (°C)
Aluminium	-159.01
Carbon steel	-156.34
Stainless steel	-156.11

The cryogenic temperature variation over time for the three materials considered is shown in Figure 5.

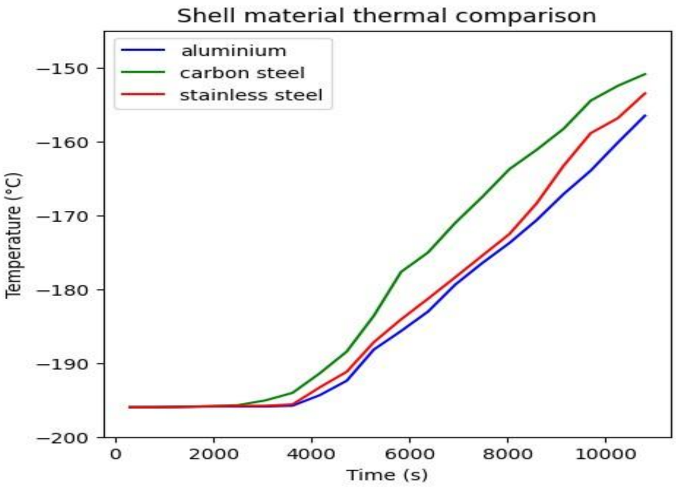

Figure 5: Cryogenic Temperature Change with Time for different Cryotank Materials

3.4 Results of Thermal Stress on Inner and Outer Shell Material

Figure 6 shows the thermal stress distribution across the inner shell of the cryotank. The stress values obtained ranged between a minimum of 63.3 MPa to a maximum of 238 MPa. The yield stress of aluminium 6061 is 276 MPa, which is higher than the maximum stress obtained from the thermal stress analysis in this study. This confirms the structural integrity of the cryotank, indicating its ability to withstand the thermal stresses generated due to high temperature differences.

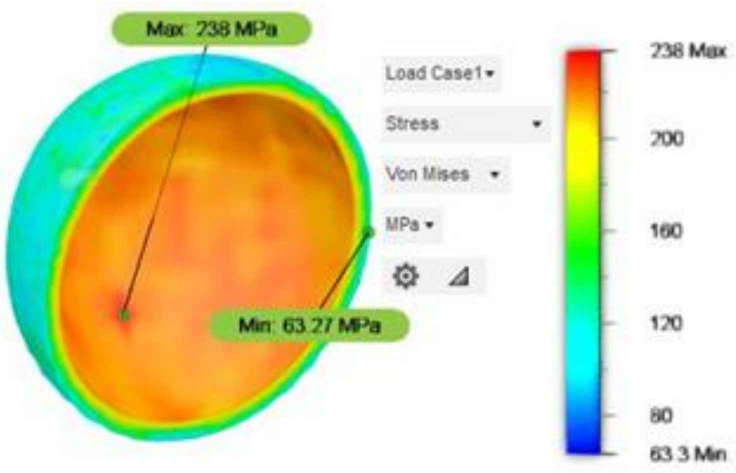

Figure 6: Thermal Stress Distribution (Aluminium Inner Shell)

4. CONCLUSION

This study focused on the numerical investigation of the geometric shape and insulation thickness for a cryotank insulated with a fibre-glass/talc-epoxy material to determine the best thermal performance based on the specified parameters. Three key factors examined were heat leakage, surface area, and minimum temperature, to evaluate the cryotank's thermal performance. The shape of the cryotank was found to have a significant impact on its thermal performance. Cryotanks with rectangular and cylindrical shapes exhibited higher heat leakage values due to their larger surface areas, whereas the spherical shape demonstrated superior thermal performance while maintaining the same inner shell volume.

The optimal insulation thickness for the different shapes of cryotanks revealed that a rectangular-, cylindrical- and spherical-shaped cryotanks achieved optimal performance with insulation thickness of 240mm, 180mm, and 160mm respectively. In terms of material selection, aluminum was identified as the optimal choice due to its excellent thermal performance and mechanical strength. This attribute allows the cryotank to withstand the thermal stress resulting from high temperature differences.

In conclusion, this numerical investigation emphasized the importance of cryotank shapes in achieving excellent thermal performance. The spherical-shaped cryotank was chosen as the best shape. Additionally, aluminum was highlighted as the preferred material when fibre glass/talc epoxy is used for insulation, considering its favourable thermal performance and mechanical strength in the cryotank's operating condition.

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