Heat Transfer Analysis of Light Weight Cryogenic Tank for Space Vehicles

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Abstract
This paper focuses on the application of light weight materials in spherical tank designs for cryogenic tanks. Two cryogenic hydrogen tank design concepts will be considered. This paper is prepared with MatLab and Abacus Version 6.10.1 and the Analysis will include thermal and structural analysis of the tank designs as well as an analysis of hydrogen diffusion to specify the material permeability requirements. Thermal modeling and analysis of a cryogenic tank design exposed to extreme heating profiles, Thermal performance comparison of insulation systems for liquid hydrogen storage tanks, Analysis of cryogenic propellant tank pressurization based upon ground experiments¹. A vacuum-jacketed design with an aluminum tank offered the most efficient thermal insulation design option. A tank design with high or low density aerogels results in a much heavier tank system, due to a higher rate of heat penetration and more propellant boil off. As such, aerogels are not a viable insulation option for the storage of cryogenic fuels.

Keywords: Aero Tank Designs, Cryogenics, Heat Transfer, Propellants

1. Introduction to Cryogenics Technology
Composite beams, plates and shells are widely used in the aerospace industry because of their advantages over the commonly used isotropic structures especially when it comes to weight savings². A number of studies have been carried out towards the application of Cryogenics in space propulsion, my studies aim at optimisation of heat transfer rate which emerges as a major problem in the storage of cryogenic fuels. Cryogenics is the science that produces very low temperatures, the temperature ranges from -150°C to -273.15°C³. It is a well known fact that, it is very difficult to obtain an absolute zero temperature and hence a temperature just above a fraction of absolute zero is only possible. Fractional distillation of air to produce nitrogen, oxygen and other gases is the area where the application of cryogenics have found its wide spread application. To obtain this air is cooled to a very low temperature to liquefy the gas present in it. The great advantage of using natural gas, oxygen, nitrogen and other gas is that it occupies less space in its liquid state as compared to its gaseous state, which is best suitable for storage and transportation in space vehicles. The two methods generally used to produce low temperature is either by magnetism and de-magnetism or compression followed by expansion of gases. In magnetism, certain materials become warm when magnetized and cold when de-magnetized. This very property of the material can be used to produce extremely low temperatures for cryogenic applications. In the compression and expansion process, we first compress a gas, remove the heat produced by compression by ordinary refrigeration and then allowing the gas to expand which further reduces its temperature. So, to produce very low temperature, two processes are important, that is compression and expansion. During liquefaction process of air, air is first compressed which thereby increases its pres-
sure and temperature, it is then allowed to cool slowly to room temperature while still maintaining the pressure. Thereafter, this cooled air is passed through heat exchanger and expanded to atmospheric pressure. This final stage of expansion brings about extremely low temperature and allows the gas to liquefy. It is a well known fact that molecules generally exist in their lowest, finest energy state at absolute zero temperature, but according the law of thermodynamics, it is not possible to reach the absolute zero due to the fact that input power required to reach absolute zero temperature approaches infinity. So, we conclude that a temperature just above (few billions) of absolute zero can be achieved by meticulously controlling the process.

1.1 Design Implements

Due to the difficulty in storing and handling of low temperature fluids that vaporizes constantly, maximum testing and experiments must be carried out with simulated fluids and hence a well defined modeling with all physical characteristics of the fluid behavior are necessary for scalability and applicability. It requires development of extensively collected data base with theoretical formulation including empirical. Thorough understanding and application of thermodynamics, heat transfer and two phase flow behavior are mandatory. Handling of two phase flow in theory as well as experiments will decide the success of the design under study.

1.2 Applications of Cryogenics

1.2.1 Cryogenics in Space

Cryogenics have widespread applications for rocket propulsions, cooling of infrared sensor, space simulation. A combination of liquid hydrogen as a fuel and liquid oxygen as an oxidizer is used in rocket propulsion due to its advantage of storing and transportation in its liquid state. Cryogenic is used as a medium for cooling infrared detectors, telescopes and probes. To obtain a good image a detector at a very low temperature is required. Infrared detectors are generally kept at a temperature lower than 80K. Similarly, the electronic circuits which are used in space vehicles are also to be kept at low temperature for enhanced performance and hence the principle of cryogenics can be adopted to maintain the temperature of these circuits. The low temperature also reduces the noise.

<table>
<thead>
<tr>
<th>Cryogen</th>
<th>(K)</th>
<th>(°C)</th>
<th>(°R)</th>
<th>(°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane</td>
<td>111.7</td>
<td>-161.5</td>
<td>201.1</td>
<td>-258.6</td>
</tr>
<tr>
<td>Oxygen</td>
<td>90.2</td>
<td>-183.0</td>
<td>162.4</td>
<td>-297.3</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>77.4</td>
<td>-195.8</td>
<td>139.3</td>
<td>-320.3</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>20.3</td>
<td>-252.9</td>
<td>36.5</td>
<td>-423.2</td>
</tr>
<tr>
<td>Helium</td>
<td>4.2</td>
<td>-269.0</td>
<td>7.6</td>
<td>-452.1</td>
</tr>
<tr>
<td>Absolute zero</td>
<td>0</td>
<td>-273.15</td>
<td>0</td>
<td>-459.67</td>
</tr>
</tbody>
</table>

The production of cryogenic temperatures almost always utilizes the compression and expansion of gases. For a typical liquefaction process of air it is first compressed, which thereby gets heated and thereafter is allowed to cool to room temperature while still being pressurized. The compressed air is further cooled in a heat exchanger before it is allowed to expand back to atmospheric pressure. This expansion process causes the air to cool and a part of it to liquefy. The remaining cooled gas available is returned through the other side of the heat exchanger where it pre cools the incoming high-pressure air before returning back to the compressor. The liquid portion of air is usually distilled to produce liquid oxygen, liquid nitrogen, and liquid argon for various purposes. The primary cryogen helium is also used in a similar process to produce even further low temperatures, but it requires several expansion cycles.
level of operation of various electronic devices. Space simulation chambers provides realistic environment of an aircraft and therefore they are cooled to cryogenic temperatures by using liquid nitrogen or hydrogen. The great challenge that the aerospace engineers face is fabrication of a product, for example, assembling a telescope at room temperature, cooling it to a low temperature and launching it in space, allowing the material to survive high vibration of launch and dimensional change of cooling down.

1.2.2 Cryogenic Insulation

The insulation system used for storage of cryogenics can be categorized according to the vacuum environments in which they are to operate. These three categories of Cold Vacuum Pressure (CVP) are listed as follows: below 0.0001 torr (0.000000133 bars) or High Vacuum (HV), from about 1 to 10 torr (up to 0.0133 bars) or Soft Vacuum (SV), and about 760 torr (1.01325 bars) or No Vacuum (NV). Materials used in high vacuum systems include aerogels, vacuum panels, MLI, LCI, perlite (fine), micro fiber glass etc\(^4\). Materials used in the newer soft vacuum systems include aerogels, LCI, and vacuum panels. Materials for no vacuum applications include foams, cellular glass, perlite, aerogels, and many others\(^5\).

2. Introduction to Experimental Work

The main aim of this Paper is the development of a generic parameterized cryogenic tank model that can employed for various purposes such as fuel tanks for rockets, uav’s, etc.

This paper presents the development of the generic parameterized cryogenic tank model by using CATIA V5 CAD software which provides tools and features for automated geometry generation and modification. In using this CAD software, two different approaches are used for the implementation of the generic model which is knowledge pattern and Power Copy with VB scripting. A comparison between both of these approaches is performed. A structural mesh generation of the generic cryogenic tank model is also created. It is ensured that the mesh elements are properly connected at the nodes and the mesh elements are of good quality.

2.1 Surface Model

The surface model of the cryogenic tank is specifically designed to be used for the finite element analysis of various fuel tanks. The surface model includes only surfaces which represent the tank shape including inner and outer surfaces\(^6\). The surface model is chosen for the finite element analysis because it is faster to do a finite element analysis on a 2D surface rather than a 3D one. It is also easier to mesh a 2D surface then a 3D one and also it is computationally beneficial. In a conceptual phase, it is also not necessary to carry out a very precise finite element analysis for the fuel tank. So, a 2D analysis will give sufficient information to be useful in the conceptual phase while saving time and resources compared to a full 3D FE analysis. The sizing of the component is accomplished by selecting the desired structural concepts and materials to be considered and specifying desired limit and ultimate factors of safety. In addition, for curved panel buckling analysis, a buckling knockdown factor and buckling lengths must be specified. The buckling knockdown factor is employed to correlate theoretical (Raleigh-Ritz) curved panel buckling loads (which are typically very non conservative) with experimental buckling loads. This is due to the fact that curved panel buckling is highly dependent on slight variations in thickness and flaws that occur randomly in structures. The necessary buckling knockdown factor is also a function of thickness, as the small variations and flaws become of greater importance as the structure becomes thinner\(^7,8\).

2.2 Solid Model

The solid model contains the solid geometry and thickness for the cryogenic tank, inner wall, outer wall and the connecting rod. The solid model can be used for the detailed design for a cryogenic tank which shows the actual thickness and geometries of the structural elements of the tank. As the surface and the solid model of the cryogenic tank are integrated together, any change in the parameters of the cryogenic tank will be reflected in both the surface and the solid model of the cryogenic tank.

2.3 Model Description

Two models have been chosen for the design of the tanks. They are 1. Vacuum-Jacketed Design and 2. Sandwiched Construction With An Aerogel Insulating Core. Both of
this models are constructed using aluminium and composite materials. The model details are shown below in the Figure 1.

Figure 1. Model of Cryogenic Tank.

2.3.1 Aluminum Tank Design

The tank design consists of two thin metal tanks separated by a vacuum gap. The outer tank provides the vacuum jacket and carries external atmospheric pressure. The inner tank contains the cryogenic hydrogen under the operating internal pressure. The design also makes use of a central rod support which passes through the center of the tanks, protruding through the tanks at the top and bottom poles. The central rod support provides structural rigidity to the inner tank, a port for filling and draining propellant, and a means of mounting the tank to the vehicle. The central rod support is approximately 10 ft long, so that the rod extends from both poles approximately 9 in., allowing enough length for mounting hardware to attach the tank to the vehicle structure. It was assumed to have a 4-in. diameter. The design described above uses the vacuum/aerogel between the inner and outer tanks as the insulation.

2.3.2 Composite Tank Design

The graphite/epoxy inner tank design consists of the spherical tank and two support tubes, one at the top and bottom poles. The support tubes provide a port for filling and draining propellant and a means of mounting the tank to the vehicle. The support tubes and spherical tank will be co-cure processed to obtain a rigid connection between the tank and tubes. To be consistent with the aluminum tank design, the outer diameter of the support tubes was 4 in. They were assumed to be 12 in. long. It was assumed that the tank assembly could be constructed such that the inner tank would be isolated both thermally and structurally from the outer tank. This could be achieved with the use of baffles between the support tubes and outer tank to maintain the insulation between the tanks and allow the inner and outer tanks to act independently in the structural sense. The design described above uses the vacuum/aerogel between the inner and outer tanks as the insulation. Silica aerogels are solid materials with extremely low density and low thermal conductivity. Unfortunately, they have very limited strength. They possess tensile strengths less than a few pounds per square inch.

3. Computational Analysis for Cryogenic Tank

3.1 Mesh Criteria

The finite element mesh of the cryogenic tank should be of good quality. This means that there are not any uneven or large angles in the mesh nodes. Furthermore, it is essential that the all the mesh elements of the cryogenic tank, inner and outer surface are properly connected at

Figure 2. Linear Triangle (3 nodes) and Parabolic Triangle (6 nodes) Finite Elements.
the nodes. This means that the growth points of the mesh be properly controlled so that the mesh elements take into account the position and orientation of the inner and outer surface and cryogenic tank. A global mesh size and tolerance parameter is defined which controls the size and characteristics of the mesh. The graphite/epoxy composite material properties used in the analyses were calculated from the fiber and matrix constituent property values and the Integrated Composite Analyzer (ICAN) code12.

3.2 Geometry of Meshing Element

The "Advanced Meshing tools" available in the generative shape structural analysis workbench in CATIA V5 software is used for creating the surface mesh of the entire cryogenic tank and performing the structural analysis. In order to perform a structural analysis on a surface, there are four types of elements are available in CATIA V5 for surfaces. They are mentioned in the Table 2 below,

Table 2. Types of Meshing Elements

<table>
<thead>
<tr>
<th>Name of Finite Element</th>
<th>Type of Finite Element</th>
<th>Mesh Connectivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear Triangle</td>
<td>Surface Element</td>
<td>3 Nodes</td>
</tr>
<tr>
<td>Parabolic Triangle</td>
<td>Surface Element</td>
<td>6 Nodes</td>
</tr>
<tr>
<td>Linear Quadrangle</td>
<td>Surface Element</td>
<td>4 Nodes</td>
</tr>
<tr>
<td>Parabolic Quadrangle</td>
<td>Surface Element</td>
<td>8 Nodes</td>
</tr>
</tbody>
</table>

4. Summary

From the above analysis the author identified the tank designs with vacuum insulation provides the best thermal insulation than the tank designs with aerogel insulation and aluminium design with vacuum insulation proves to be the best among all.

<table>
<thead>
<tr>
<th>MATERIAL/INSULATION</th>
<th>VACUUM</th>
<th>AEROGEL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Heat Flux Due To Conduction</td>
<td></td>
</tr>
<tr>
<td>ALUMINIUM</td>
<td>1.953e+02</td>
<td>9.807e+01</td>
</tr>
<tr>
<td>COMPOSITE</td>
<td>1.815e+02</td>
<td>7.815e+01</td>
</tr>
</tbody>
</table>

5. Conclusion

In the assessment of the various thermal insulation approaches, it was established that a vacuum-jacketed design with an aluminium tank offered the most efficient thermal insulation design option. A tank design with high or low density aerogels results in a much heavier tank system, due to a higher rate of heat penetration and more propellant boil off. As such, aerogels are not a viable insulation option for the storage of cryogenic fuels. Therefore the analysis show that the thermal insulating superiority of a vacuum-jacketed design over high or low density aerogel designs. Therefore we can conclude that an aerogel is not a viable design solution.

6. Reference


