International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 2 Issue 11, November - 2013

Thermo structural analysis of high pressure cryogenic tank

*S. Murugan [a] M.S. Starvin [b] K. Muruga Dhas [c]
[a] *Graduate Student, M.E (CAD), University College of Engineering, Nagercoil – 629004*
[b] *Asst. Professor, Dept. of Mechanical Engineering, University College of Engineering, Nagercoil*
[c] *Scientist/Engineer, Liquid Propulsion Systems Centre, Mahendragiri – 627 133*

Abstract

In this paper, thermo-structural analysis of high pressure cryogenic tank (liquid hydrogen tank) is presented. The chill-down process is performed on a 9.6m^3 *Water Capacity (WC) and 22 MPa Maximum Allowable Working Pressure (MAWP) hydrogen tank with controlled rate of cooling. The finite element analysis (transient thermal and structural) of hydrogen tank is performed with ANSYS Software. This analysis incorporates temperature dependant material properties, temperature and pressure variations across the height of the tank during chill-down with liquid Nitrogen (LN2) followed by liquid Hydrogen (LH2) for analyzing behavior of the tank. Temperature distribution of the tank and magnitude are obtained and used for estimation of transient heat transfer, induced thermal stress, structural stress, distortion in the material due to chill-down and pressurization. In order to avoid thermal crack, chill-down at controlled rate of cooling restricting temperature difference across the tank height is maintained.*

***Keywords**:* Chilldown, High pressure cryogenic vessel, Liquid hydrogen tank, Pressurization, Transient thermal analysis.

1. Introduction

The term “Cryogenic” refers to the field of science that deals with behaviour of substances at temperature below 123 K. This is a logical dividing line, because the normal boiling points of permanent gases such as helium, hydrogen, neon, nitrogen, oxygen and air lies below 123 K, while the Freon refrigerants, ammonia and other conventional refrigerants all boil at temperature above 123 K [1]. The principal sources of the cryogenic fluid are atmospheric air and natural gas. Cryogenic fluids find applications in many engineering fields and medical science viz. space application, super conductivity, high vacuum technology, biological and medical applications, food processing, manufacturing process, recycling of material, etc. The use hydrogen in an internal combustion engine or in a fuel cell substantially increases the efficiency.

A cryogenic experiment or system is normally dominated by the need to get something cold and keep it cold, with other element of the design subservient to that. Providing a cryogenic environment is the critical task in cryogenics. Every cryogenic experiment needs some way of reaching low temperatures. There are two ways of doing this; using cryogens or using mechanical coolers, with a liquid cryogen, evaporation of the liquid maintains the temperature at the boiling point, and this is how the majority of cryogenic experiments are cooled and kept cold, though mechanical cryogenic coolers have become more popular in recent years [2]. Cryogens provide cooling in two ways (i) Heat is used in evaporating the liquid - it absorbs latent heat. (ii) Heat is then used in warming the gas from the boiling point to room temperature; the heat required to do this is given by the enthalpy change [2]. The main cryogens in use in cryogenics are helium, nitrogen and hydrogen etc.

Hydrogen has been well recognized as a powerful and clean energy fuel for a few decades, especially for space applications. Although it has many advantages over most conventional fuels, efficient storage of hydrogen is difficult because of its very low density [3]. Liquid storage of hydrogen has a significant advantage over gaseous or chemical storage because of its much lower storage volume and associated tank mass, which is especially important for space applications. Conventional cryogenic storage tanks suffer loss of liquid hydrogen due to boil-off of the cryogen induced by heat leakage into the tank from the warmer surrounding environment [3]. Boil-off is allowed to maintain the cryogen pressure within the structural limits of the tank. The goal is to store the hydrogen fuel for a very long time without loss.

LH2 is an odorless, colorless liquid that alone will not support combustion. In combination with oxygen or air, hydrogen is flammable. The mixtures of hydrogen-air are explosive in an unconfined space in the range from 18 to 19 % hydrogen by volume.

The risk of handling this considering the safety [2] [13] cryogenic tanks must be well designed and engineered by incorporating the thermal behavior of the material used for the cryogenic tanks [4].

Table 1
Selected properties of the cryogenic liquids at normal boiling point

Saturated Liquids	LH2	LOX	LN2	LHe
Normal boiling point (K)	20.27	90.18	77.36	4.21
Critical temperature(K)	33.2	154.6	126.1	5.2
Critical pressure(bar)	13.15	50.8	33.9	2.29
Triple point temperature(K)	13.9	54.4	63.2	-
Triple-point pressure(bar)	0.072	0.002	0.129	-
Density (kg/m^3)	70.79	1141	807.3	124.8
Latent heat (kJ/kg)	443	213	199.3	20.9
Specific heat (kJ/kg-K)	9.68	1.695	2.05	4.48
Viscosity (μPa-s)	13.2	190	158	3.56
Thermal conductivity (mW/m-K)	118.5	151.4	139.6	27.2

In recent years, a number of efforts have been made in the development of good cryogenic storage systems. The major milestone was to identify the cooling down effect of the tank considering the material properties and strength design at very low temperature. Jelliffe Jackson presented Transient Heat Transfer during cryogenic chill down [6] which studied the heat transfer effect in the flow boiling regime. Javad Marzbanrad and crew from IUST [7] had analyzed the composite high pressure storage vessel which is used in automotive systems. In 2007 Robert C. Youngquist from Kennedy Space center [8] studied the heat transfer effects on hydrogen storage tanks. Xia Yen Wang and crew from Glenn Research Centre [9] had done an axis symmetric analysis for the heat transfer in Hydrogen tank for UAV system. Many other thermal analysis [10] [11] [12] are done in spherical shaped hydrogen tanks.

This paper presents the thermal and structural effect of chill down in the temperature dependant material. Temperature dependant material properties [4] temperature and pressure variations across the surfaces of the tank during chill-down with liquid Nitrogen (LN2) followed by liquid Hydrogen (LH2) is used for analyzing behavior of the tank. Temperature distribution of the tank and magnitude are obtained and used for estimation of transient heat transfer, induced thermal stress, structural stress, distortion in the material due to chill-down and pressurization.

The high pressure hydrogen tank is thick-walled vessel and can be warmed up during pressurization and cooled down prior to the filling with LH2. Before admitting liquid hydrogen in to the tank, it is mandatory to chill down the hydrogen tank from ambient condition to close to the boiling point of liquid hydrogen in order to avoid thermal stresses that may develop upon cooling of tank wall. Chill-down of the hydrogen tank is done in 2 stages i.e. initially with LN_2 the tank is cooled from ambient temperature to close to the boiling point of LN2 (77K) and finally cooling with LH2 and bring down the temperature close to 20 K. While performing chill-down operation of the tank, the following challenges are considered: (i) rate of temperature fall is restricted to 30K per hour (ii) difference in temperature of bottom and top of the tank should not exceed 80K at any point of time.

The temperature difference, occurring in such case between the layers, causes additional temperature stresses. Hence the process of chill-down of LH2 tank from ambient to liquid hydrogen temperature is considered for analysis.

2. Model description

The high pressure LH2 tank is of 9.6 m^3 Water Capacity (WC) and 22 MPa Maximum Allowable Working Pressure (MAWP) made of austenitic stainless steel and consists of thick-walled (110 mm) cylindrical shell with hemispherical dished ends of 80 mm thick and is rested on the four tubular supports in the bottom part of dished end. The top end of tank is covered with protective shield against convective heat transfer of gaseous hydrogen [5].

The hydrogen tank is enclosed by a cylindrical jacket with elliptical ends made of High Grade steel and rested on a common foundation by a standard cylindrical support. The supports shell at the top is welded to the jacket end and at the foot the same is welded to the bottom ring of support. The foot ends of the tubular supports are welded to the given rings. The hydrogen tank is thermo-insulated by screen-vacuum type of insulation (SVTI) with alternate Layers of reflective and space materials. The type of reflective material is metalized polyethylene terephtalate film. The thickness of screen-vacuum type of insulation is 38 mm.

During chilling, temperature of the vessel wall is monitored using array of eight temperature sensors mounted throughout the height of the tank at discrete distances to control the rate of chill-down.

Table 2
Specifications of Hydrogen tank

Major dimensions	
Internal diameter	1600 mm
Thickness of cylindrical shell	110 mm
Thickness of dome	80 mm
Gross volume	9.6m3
Usable volume	9.0m3
Material of construction	SS321
Dry mass	25 MT
Insulation	screen-vacuum (SVTI)
Evaporation loss rate	2%per day

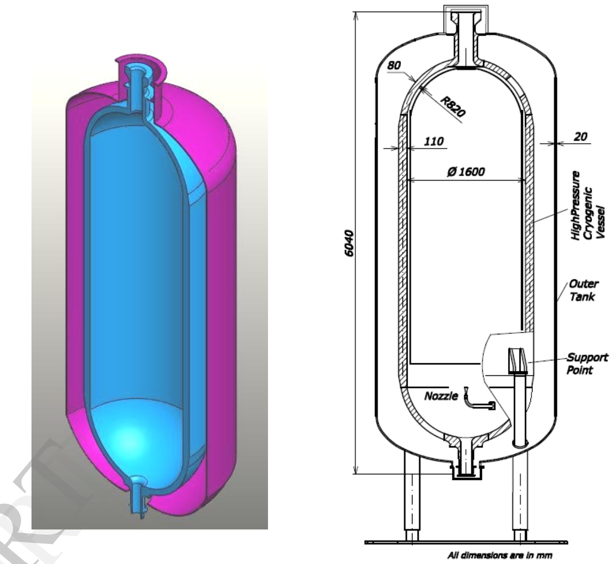
The hydrogen run tank is fitted with a bubbler and vaporizer, with the help of which the warming-up of liquid nitrogen occurs to the temperature, which corresponds to the equilibrium condition. The system of pipelines includes the manual flow and safety relief components, thermo-insulated pipelines. The instruments are available for the control of parameters of set.

2.1. Objective of calculation

The objective of calculation is (i) determination of temperature distribution across the height of LH2 tank during chill-down; (ii) to calculate the induced thermal stress during chill-down and also calculate the stress concentration during pressurization.

Data considered in the process of chill down are

(a) The geometrical sizes of vessel are taken from the drawings.
(b) The pressure of LN2 before the nozzles is 0.8 MPa.
(c) The pressure of LH2 before the nozzles is 0.4 MPa.
(d) The process of chill –down through nozzles by LN2 or LH2 in the saturation line.
(e) The chill-down is firstly carried out by nitrogen, then by hydrogen via the two nozzles of Laval type nozzle.



a) 3-D Model **b) Essential dimensions**

Fig. 1 Cross sectional view of hydrogen tank

2.2. Chill-down process

The high pressure LH2 tank is thick-walled cylindrical tank with hemispherical dished ends and can be cooled down prior to the filling with LH2 and warmed up at the pressurization. The temperature difference, occurring in such case between the layers, causes additional temperature stresses. This circumstances call for regulated dynamically controlled rate of cooling. The chill-down cycle followed is presented below:

The chill-down of LH2 tank is performed initially by way of admitting LN2 through pair of special convergent divergent laval nozzles which is placed at the bottom of the tank at a pressure of 0.8 MPa. The LN2 enters the nozzle and after expansion form two-phase flow consisting of liquid droplets dispersed in vapour. The LN2 after expansion travel through surface of the tank and take the heat of the tank first at bottom of the tank and flows over the surface of the tank and travel upward due to natural convection. Since the heat transfer depends on the velocity of gas constituent of flow and may vary over the range 100 to 600 W/m^2K.

In this case uniform chill-down along the entire surface of vessel is ensured. During the process of chill-down of the tank by LN2 care must be taken for thermal management of tank (i.e) the rate of cooling should not exceed 30K/hr and dynamic control of difference in temperature across the tank height should not exceed 80K at any point of time. If by any chance the temperature across the wall exceed the above constrain then supply of LN2 will be restricted and the tank will be allowed to normalise the temperature due to conduction. It is possible to bring down the temperature of the tank from ambient to close to the boiling point of LN2 i.e 77 K using LN2. Then LH2 is used to bring down the temperature of tank further close to boiling point of LH2 (20K). Once the tank reaches close to the temperature of 20K, LH2 is admitted in to the hydrogen tank.

2.3. Material properties

The variable material properties of high grade austenitic stainless steel 321 (SS321) [4] [12] are considered for the transient thermal analysis which is taken from the fig.2. The temperature range considered is from 4.2 K to 340 K. The Poisson ratio of the tank material is kept constant as 0.3 throughout the analysis. Density of the material considered is 7900 kg/m^3.

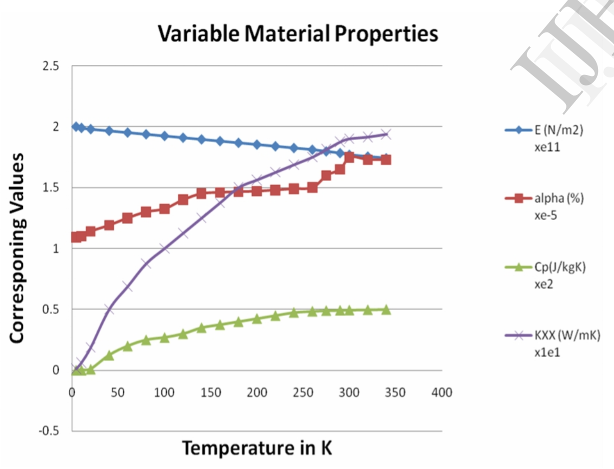


Fig.2 Variable Material properties

3. Finite Element model

The objective of transient thermal and structural analysis is to find out thermal stress induced during chill-down and stress induced during pressurization. For doing transient thermal analysis an axi-symmetry model of the hydrogen tank is created to dimensions using geometry tool of ANSYS Software. A small strip of element is considered for calculating the temperature distribution and 180 degree revolved 3D element is used for applying transient thermal and structural loads. For a 3-D domain of irregular shape, it is easier to generate a mesh of tetrahedral elements. The use of such elements yields significant increase in the number of elements, giving more accurate results. In this 3D model analysis tetrahedral element size of 0.05 m is used for creating 136272 elements and 191435 nodes.

The model is sub-divided in to 8 segments across its height and 8 numbers of temperature probes are inserted at appropriate places and designated as RTC 200 to RTC 207 for applying transient thermal load. Necessary supports at appropriate places are provided as per fig.1. Process end is fixed as 90 hrs in line with the total chill down duration at low flow rate of cryogen. Considering this total no of step is set as 90 steps. Each step represent one hour duration. Step end time is given as 3600 s in order to obtain results of transient thermal data and temperature distribution pattern at every one hour.

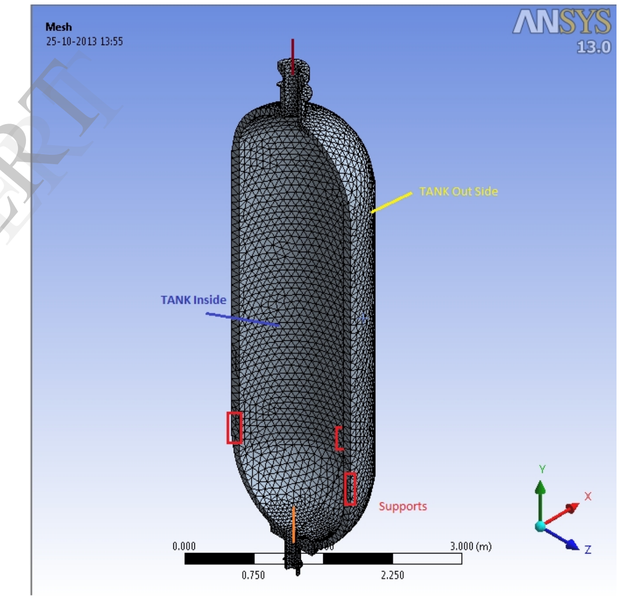


Fig 3. FE Model of Hydrogen tank

Heat transfer at the free convection of nitrogen in the bottom part of LH2 tank calculated for the following two boundary temperatures with a gauge length of 1 m are (i) 323 K and 100 K (ii) 150K to 80K.The Rayleigh Number (Ra) can be calculated using the following empirical formula.

$$Ra = \frac{9.81 \cdot {}^{\circ}{}_{1}^{2} \cdot C_P \cdot \Delta T \cdot h^3}{\text{«} \cdot {}^{\text{a}} \cdot T_{G\_sr}} \qquad (3.1)$$

Where C_p is specific heat at const. pressure, ΔT difference in temperature, ρ density, h gauge length, μ coefficient of viscosity, λ gas heat transfer factor, α coefficient of heat transfer and T is film temperature.

The coefficient of heat transfer in W/ (m^2×K) is determined by Nusselt Number (Nu) by the equation (5.2)

$$\sim\ = Nu\cdot\frac{\text{a}}{h} = 0.13\cdot\left(Ra\right)^{\frac{1}{3}}\cdot\frac{\text{a}}{h} \tag{3.2}$$

The convective heat transfer coefficient in the bottom part of LH2 tank at the chill-down using LN2 is calculated by the formulae (3.1) & (3.2) and weakly depends on the wall temperature and hence nearer value of convective heat transfer coefficient is taken as **13 W/(m^{2}òK).**

Heat transfer at top part of LH2 tank takes place through shield. In this case the Rayleigh number (Ra1) is calculated for the following two boundary temperatures with a gauge length of one metre are (i) 323 K and 100 K (ii) 150K to 80K. The Ra 1 value can be calculated using equation (3.1). The equivalent thermal conductivity of the shield and the heat transfer coefficient for those above boundary temperature range are calculated using the formula (3.3) and (3.4) respectively.

$$\text{a}\ = \text{a}1\cdot Nu1 = \text{a}1\cdot\frac{0.071}{\left(\frac{h}{\text{¢}}\right)^{\frac{1}{9}}}\cdot Ra1^{\frac{1}{3}} \tag{3.3}$$

The overall heat transfer coefficient is determined by the formula:

$$k = \left(\frac{\text{¢}}{\text{a}} + \frac{1}{\sim}\right)^{-1} \tag{3.4}$$

The heat transfer coefficient at the top of LH2 tank at the chill-down using LN2 is calculated by the formulae (3.1), (3.3) and (3.4) and weakly depends on the wall temperature and hence nearer value of heat transfer coefficient is taken as **3 W/(m^{2}òK).**

Similar calculations are made for finding the heat transfer at the free convection of Hydrogen in the bottom part and top of the LH2 tank and calculated for the following two boundary temperatures with a gauge length of one metre viz (i) 323 K and 100 K (ii) 150K to 80K using the equations (3.1) to (3.4) and the results are as follows:

The convective heat transfer coefficient in the bottom part of LH2 tank at the chill-down using LH2 is calculated as **34.88 W/(m^{2}òK).**

The heat transfer coefficient at the top of LH2 tank at the chill-down using LH2 is calculated as **3 W/(m^{2}òK).**

For maximum factor of Heat transfer the convective heat transfer coefficient in the bottom part of LH2 tank at the chill-down using LN2 is calculated by the formulae (3.1) & (3.2) and weakly depends on the wall temperature and hence nearer value of convective heat transfer coefficient is taken as **17 W/ (m^{2}òK) in** the bottom and upper part of the vessel.

The convective heat transfer coefficient in the bottom and top part of LH2 tank at the chill-down using LH2 is calculated as **50 W/(m^{2}òK).**

3.1 Thermal & Structural analysis

Transient thermal & structural analysis is carried out for obtaining stress due to chill-down and pressurization. The convective heat transfer coefficient obtained through numerical calculation is applied as load at inner surface. The boundary conditions given for transient thermal and structural analysis are shown in Table 3.

The variation of temperature distribution over time is of interest in many applications such as chill-down of cryogenic vessels, pressure vessels, cooling of electronic packages or a quenching analysis for heat treatment. Also of interest are the temperature distribution results in thermal stresses that can cause failure. In such cases the temperature from a transient thermal analysis are used as inputs to a structural for thermal stress evaluation.

Many heat transfer applications such as heat treatment problems, electronic package design, nozzles, engine blocks, pressure vessels, fluid-structure interaction problems and so on involve transient thermal analysis.
A transient thermal analysis can be either linear or nonlinear. Temperature dependent material properties (thermal conductivity, specific heat or density) are provided as per fig 2. These data can result in nonlinear analyses that require and iterative procedure to achieve accurate solution. The mechanical application allows applying temperature from thermal analysis as loads in a structural analysis for thermal stress evaluation.

During structural analysis of the tank for the pressurization, temperature distribution of chilldown tank is imported to give combined effect of thermal and structural analysis (Coupled Analysis).

Table 3
Boundary conditions for transient analysis

Condition during chilling	
Material properties	As per fig 2
Inner side of the vessel	Convective heat transfer
Outer side of the vessel	Screen Vacuum (SVTI)
Initial temperature	305 K
Thermal Source/ Load	Heat generated due to convection
Process duration	90 hrs
Constrains & Supports	four fixed supports at locations as in fig 1
Model type	3D Symmetric
Element size	0.05 m
No of elements	136272
No of nodes	191435
Condition during pressurization	
Inner side of the vessel	0.1MPa to 20 MPa
Outer side of the vessel	1 Pa
Body Temperature	Min 15K, Max 350K
Medium of chilling	LN2 and LH2
Model type	3D Symmetric
Process duration	75 s
Constrains & Supports	four fixed supports at locations as in fig 1

4. Results & Discussions

The thermo structural analysis of high pressure cryogenic tank is thus modelled with convective heat transfer coefficients for bottom and top portions of the liquid hydrogen tank. The range of flow maintained for LN2 is 0.4 to 0.02 kg/s and that of LH2 is 0.2 to 0.008 kg/s through nozzles. The coefficients of heat transfer for chill-down with LN2 & LH2 are given as input for ANSYS and results are obtained. Post processing is done to interpret the results and presented in the following paragraphs.

Temperature distribution across the tank height over time is plotted, which shows the regions where the tank gets maximum chilling at each hour. These values are directly incorporated for determining the thermal stress analysis. For structural analysis of tank during pressurisation, the body temperatures at the 90th hr are imported throughout the analysis since the pressuring gas temperature effect is negligible due to the presence of the shield which is present in the wall and top end cover of the tank.

Maximum temperature at each hour is found at the top end cover of vessel due to natural convection effect due to flow of LN2 and LH2 inside the tank walls upwards and through the shield at top portion.

The temperature distribution across the height of LH2 tank during chilldown process are obtained and presented in fig.4 to fig.13. The maximum value of thermal stress induced is 586 MPa at 90th hr of chilldown, and which occurs at the support points as presented in fig. 14.

Stress developed due to pressurisation is plotted in fig.15. Maximum stress induced due to pressurisation at the support points which is well below the maximum stress value of the material at cryogenic temperature.

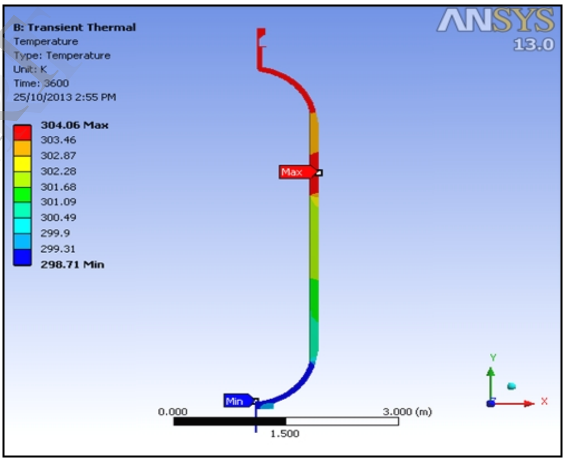


Fig.4. temperature distribution at 1st hr

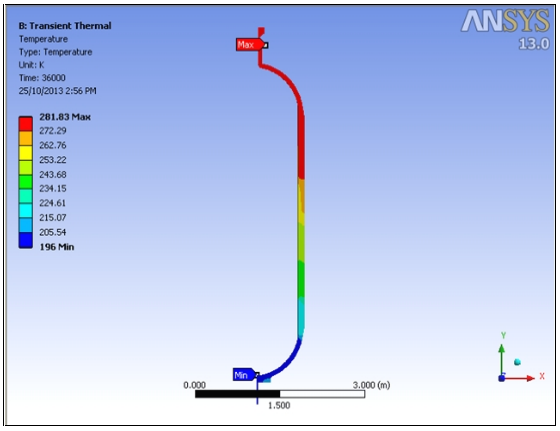


Fig. 5 Temperature distribution at 10th hr

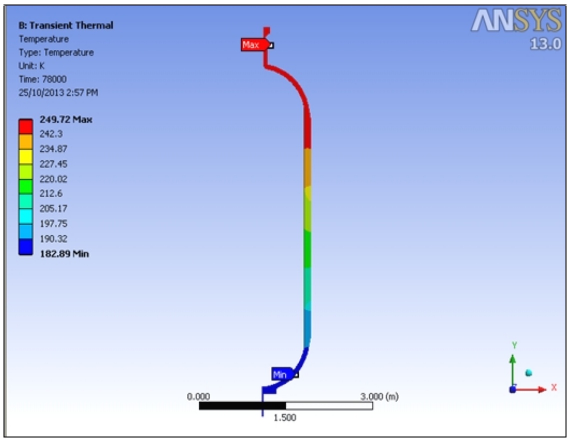


Fig. 6 Temperature distribution at 20th hr

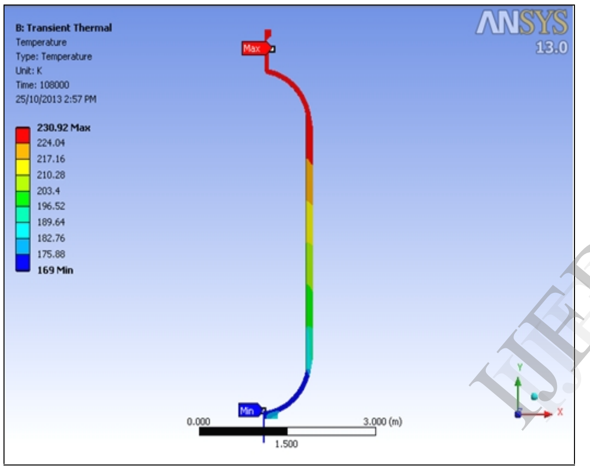


Fig. 7 Temperature distribution at 30th hr

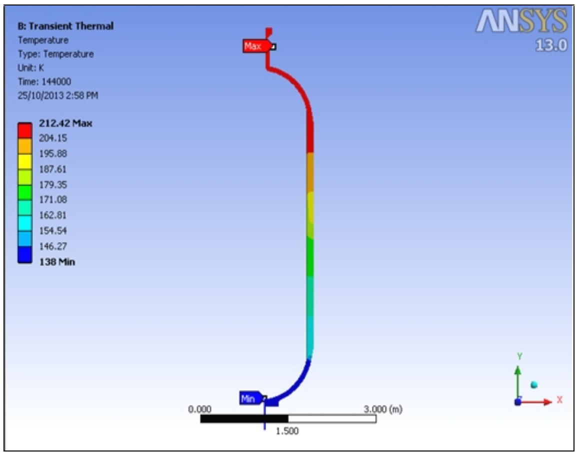


Fig. 8 Temperature distribution at 40th hr

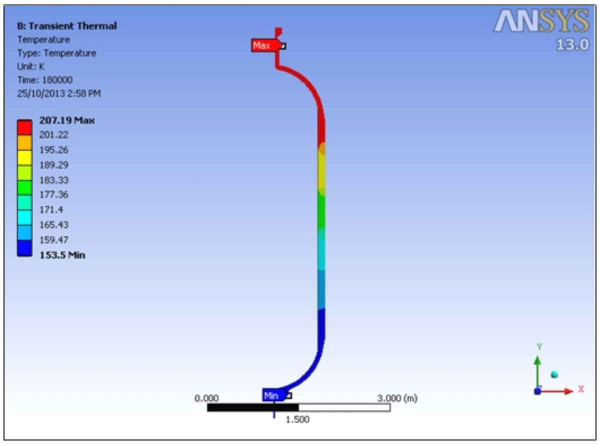


Fig. 9 Temperature distribution at 50th hr

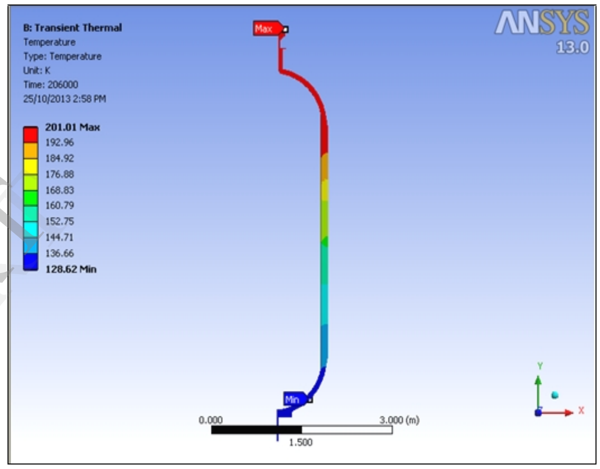


Fig. 10 Temperature distribution at 60th hr

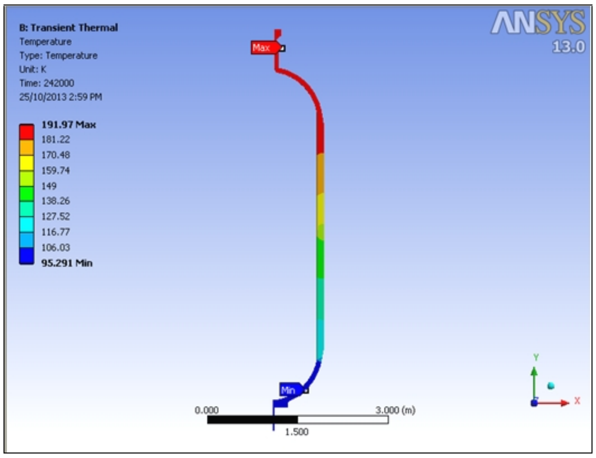


Fig. 11 Temperature distribution at 70th hr

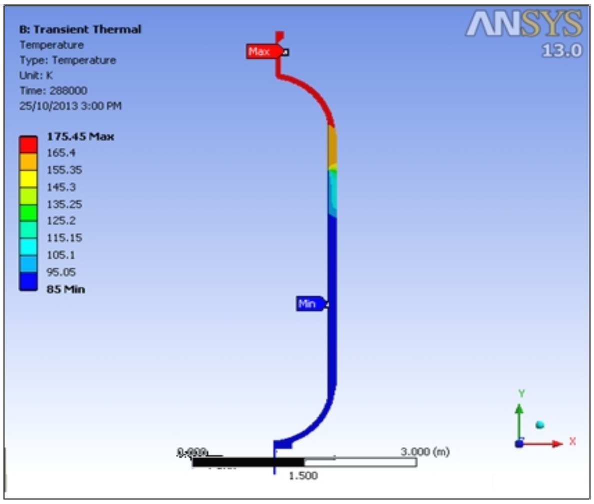


Fig 12 Temperature distribution at 80th hr

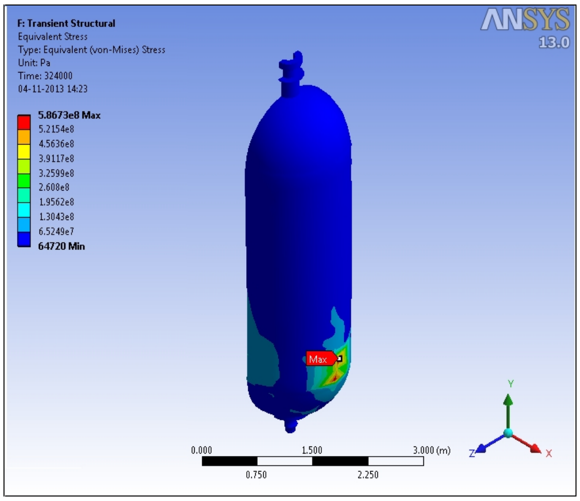


Fig. 14 Result of Thermal Stress developed due to chilldown.

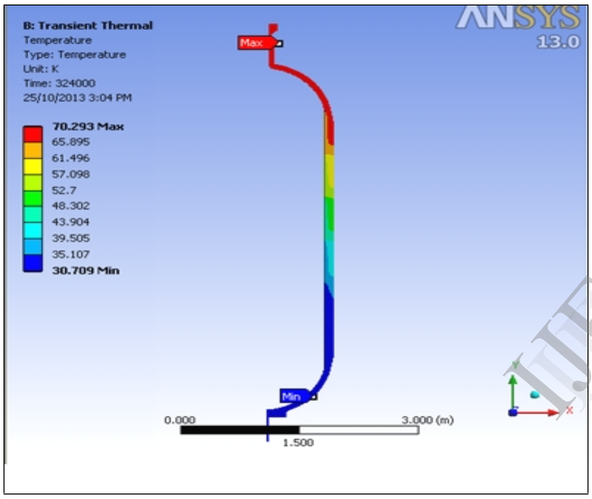


Fig.13 Temperature distribution at 90th hr

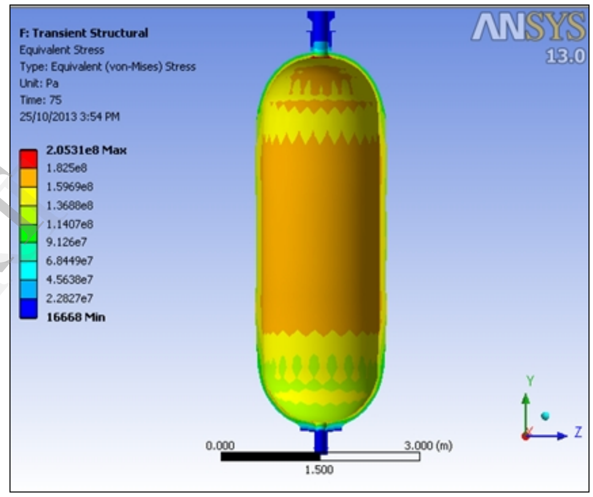


Fig. 15 Stress formation due to Pressurisation of tank

During the pressurisation process the tank is being kept under a pressure 1 MPa to 20MPa. This effect of high pressure creates heavy structural loads on the thermally contracted tank vessel. The maximum stress formation is occurred at top end region where temperature is comparatively high compared to the other regions of tank. The maximum value 205MPa is under permissible limit for the material, thus the above procedure of cool down is found safe.

5. Conclusion

(i) The time required for chill – down of hydrogen tank is theoretically found to be 90 hours (~4 days) to 35 hours (~2days) depending upon the intensity of circulation that develops in the vessel.

(ii) The most part of time for cool-down is spent for nitrogen cool-down. When the chill-down duration is 90 hours that is at low flow rate of Nitrogen at 0.02 kg/s and Hydrogen at 0.008 kg/s. Chilldown time of 80 hrs operation is spent with Nitrogen and 10 hrs is spent with Hydrogen.

(iii) When the chill-down duration is 35 hrs that is at high flow rate of Nitrogen at 0.4 kg/s and Hydrogen at 0.2 kg/s.; in this case chilldown with Nitrogen is 30 hrs and with Hydrogen 5 hrs.

(iv) It is understood from the analytical results that rate of chill-down depends on the capability of wall to evaporate the liquid nitrogen and liquid hydrogen.

(v) The range of flow rate for cool down are as follows: For Nitrogen 0.4 to 0.02 kg/s; For hydrogen from to 0.2 to 0.008 kg/s

(vi) Stress developed due to the chilling down process is found to be maximum at the supports 586 MPa, which occurs at localized spot and permissible due to stress redistribution in plastic flow.

(vii) Pressurisation (1MPa to 20MPa) process is conducted for a total duration of 75s considering the maximum time including fluid withdrawal time. Thus the effect is more realistic and the stress developed 205MPa is within the permissible limits for the material at cryogenic temperature.

6. References

[1] Randall F. Barron, text book of Cryogenic Systems, Dept. of Mechanical Engineering, Louisiana, USA.

[2] Adam L. Woodcraft, “An introduction to Cryogenics”, SUPA institute of Astronomy, Edinburgh University, Blakford Hill, UK; Oct 2007

[3] Son. H. Ho, Muhammad M. Rahman, “Three-dimensional analysis for liquid hydrogen in a cryogenic storage tank with heat pipe–pump system” Department of Mechanical Engineering, University of South Florida, 4202 E. Fowler Avenue, Tampa, FL 33620, USA; Science Direct- Cryogenics 48 (2008) 31–41; Sep 2007

[4] Materials for Cryogenic Service- Engineering properties of austenitic stainless steel- Distributed by the Nickel Development institute, courtesy of Inco Limited; Published in 1974

[5] A. Narayanan, “Cryogenic Rocket Engine Thrust Chamber test facility” Liquid Propulsion Systems Centre, Mahendragiri, Tamilnadu, India; Jan 2013

[6] Jelliffe Jackson et al “Transient heat transfer during cryogenic chilldown” Department of Mechanical and Aerospace Engineering, University of Florida, Gainesville, Florida 32611, USA; July 2005

[7] Javad Marzbanrad, Amin Paykani, Amir Afkar, Mostafa Ghajar “Finite element analysis of composite high pressure hydrogen storage vessels” School of engineering, Iran University of Science and Technology (IUST): ISSN:2028-2508 J Master Environ. Sci 4 (1) 2013 63 -74; Sep 2012

[8] Robert C. Youngquist “Pad B Liquid Hydrogen Storage tank” Kennedy Space Centre; Aug 2007

[9] Xia-Yen Wang, George Harpster and James hunter “Thermal Analysis on Cryogenic Liquid Hydrogen Tank on an Unmanned Aerial Vehicle System” Glenn Research Centre, Cleveland, Ohio: NASA/TM 2007 -214675 AIAA -2007 -1218; Jan 2007

[10] Craig A. Stephens et al “Thermal-Fluid Analysis of the Fill and Drain Operations of a Cryogenic Fuel Tank”, NASA Technical Memorandum 104273, NASA-Dryden Flight Research Facility, Edwards, California 93523-0273; Dec 1993

[11] Craig A. Stephens et al “Thermal-Modelling and Analysis of a Cryogenic Tank Design Exposed to Extreme Heating Profiles”, NASA contractor report 186012, NASA-Dryden Flight Research Facility, Edwards, California 93523-0273; Dec 1991

[12] Stanley S. Smeltzer III et al “Nonlinear Thermal Analyses of a liquid hydrogen tank wall” NASA Langley Research Centre, Hampton, VA:

[13] Physics division cryogenic safety committee “Physics Division Cryogenic Safety Manual” Argonne National Laboratory, Argonne, Illinios60439; Sep 2001

[14] Donald Greer, “Cryogenic fuel tank draining analysis model”, NASA Dryden Flight Research Centre, Edwards, California ; July 1999

[15] Oludele Adeyefa, Oluleke Oluwole “Finite Element Modelling of Insulation Thickness for Cryogenic Products in Spherical Storage Pressure Vessels”, Scientific Research, Vol 4, No.6; Jun 2012