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Thermo-Structural Response of a Rocket Thruster Using Fem

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Abstract— Rocket Thruster is a reaction control system of liquid rocket propulsion system, used for the attitude control of missile. The reaction control system is employed in the missile to provide roll control to the second stage after separation of the first stage. The thruster is subjected to temperature and pressure loads during its operation. It is essential for a flight vehicle to have low weight and high velocity to overcome the gravity. In order to develop compact size thruster, it is required to carry out structural analysis for SS321 material. The present report deals with analysis of Rocket Thruster casing and flange joint. The Rocket Thruster casing is designed as per ASME pressure vessel code and NASA SP 125 design report. The proposed model is a modification from the conventional joint between L-dome and injector plate. Thermo-structural analysis is performed to evaluate the new design which eliminates use of welded joint. Analysis is carried out to estimate stresses especially in the modified region to ensure less stresses are developed compared to the original design. Analysis has been carried out considering the external injector pressure for shell and then the temperature loads are applied on the thruster to estimate the deformations and stresses. The Thruster is then subjected to a thermo-structural load and then von Mises stresses are estimated.

Key Words— Finite Element Method, Thermo-structural response, Rocket Thruster

I. INTRODUCTION

A thruster is a propulsive device used by spacecraft and watercraft for station keeping, attitude control, in the reaction control system, or long-duration, low-thrust acceleration. Thrusters are located around the nozzle to direct the control system. These are called Reaction Control Systems (RCS). The RCS is used for the control of flight vehicles flying at low dynamic pressures, i.e. low enough for good performance of aerodynamic control surfaces. The Reaction Control System thruster is employed in the missile to provide Roll control to the second stage after separation of the first stage. Thrust Chamber houses main injector. It atomizes mixes, ignites and ultimately promotes the complete combustion of liquid propellants. The thrust chamber assembly of thruster generates power by combusting liquid propellants raised to the required combustion pressure by propellant feed system. The combustion products are discharged through converging – diverging nozzle to achieve high gas velocity and thrust. Thrusters control the Roll, Pitch and Yaw directions of the vehicle.

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As rule of ASME Pressure vessel code section VIII division 2, such a rocket thruster has the following five major components, shell, L-dome, oxidizer adaptor, fuel adaptor, and injector plate.

The purpose of dome is that the primary air flows through as it enters the combustion zone. Their role is to generate turbulence in the flow to rapidly mix the air with fuel.

An adaptor is a device that converts attributes of one device or system to those of an otherwise incompatible device or system. When there is a fuel tank and an engine both connected to the adaptor on different sides, propellants, like liquid fuel and oxidizer, will flow through the adapter on the way to the engine. Fuel adaptor fits the fuel filler neck at one end, and with an outsized diameter at the other end, allows fueling from larger nozzles.

The last component, the injector plate, is located in general, at the forward end of combustion chamber. The function of an injector is similar to that of the carburetor of an internal combustion engine. The injector introduces and meters the propellant flow to the combustion chamber, and atomizes and mixes the propellants for satisfactory combustion.

II. LITERATURE REVIEW

Nowadays, the space trip business in the private sector aiming at weightless experience is becoming a reality in Europe and the United States."Space Ship One" or "Space Ship Two" systems are well known at present to the general public. Although all space vehicles under development are based on the chemical rocket engine system, each company adopts its original launch system.

The catalytic decomposition of nitrous oxide for spacecraft application is gaining interest in the propulsion community [1-3] because nitrous oxide decomposes exothermically. Its potential for use in monopropellant, resistojet, and bipropellant thruster applications has been already introduced by several researches [4-5], not to mention its application for use in the catalytic igniter [5-8], of Hybrid Rocket Motor (HRM).

The spark igniter operated by inflammable gas often induced combustion instability by pressure oscillation and has difficulty changing the inflammable gases to oxidizer, based on environmental conditions [9, 10]. Therefore, several researchers have focused on Nitrous Oxide (N_2O) catalytic igniter because it is a more reliable ignition system for hybrid rockets. Recently zakirov and martin [5, 6, and 8] and zakirov et al. [7] presented the feasibility of using an N_2O catalytic igniter consisting of packed bed as a hybrid ignition system.

At the beginning of this century, the concept of vortex combustion cold-wall thrust chamber was conceived by the scientists of Orbitec Corporation [11, 12].

For a new-concept rocket thruster, the basic features of the coaxial vortex flow field have been observed empirically [11-14] and analyzed both theoretically [15- 21, 25] and numerically [22-24].

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Very few studies have focused on experiments except Ref.[20]. In their study, Craig et al. used PIV to study the influence parameters for gelled propellants rocket thruster.

A variety of recent works account for the growth in knowledge and technique in the assessment of the structural behavior of SRM nozzles. A study on the initial phase of transient thermal stresses due to general boundary thermal loads in orthotropic hollow cylinders was carried out by Kardomateas G.A [26].

Mukherjee and Sinha [27] carried out an investigation into the thermo structural behavior of rotationally symmetric multidirectional fibrous composite structures using the finite element method.

David Heckman [28] in 1988 has explored that the finite element analysis is an extremely powdery tool when used correctly. For pressure vessels finite element analysis provides an additional tool for use in analysis. However, it must be compared to other available data, not taken as being correct just because it looks right.

. In the present work an attempt has been made to study the two designs of rocket thruster under static and static coupled with thermal loading for developing a compact size thruster and design modification.

III. GEOMETRIC MODEL

A. Requirements for Thruster Design

The required parameters that are considered for the design of rocket thruster are

- Shell thickness
- Injector plate thickness
- Flange thickness

The above required parameters are considered from the drawings provided by DRDL, Hyderabad and these parameters are verified with the ASME pressure vessel standards to specify that they are within the safe limits.

ASME Pressure vessel code section VIII division 2 gives the formula for the calculation of shell and injector plate thickness and is given below

Thickness of shell is given by

$$T = \frac{P\ x\ D}{2\ x\ (SE-0.6P)} \quad \text{--------} \ (1)$$

Where

P - Internal Design Pressure = 100 Bar = 1.0 Kg/mm^2

S - Allowable stress in Kg/mm^2

E - Efficiency taken equal to 100%

Injector Plate thickness is given by

$$T = d\sqrt{\left(\frac{CP}{SE} + \frac{1.9whg}{SEd^3}\right)} \quad \text{---------} \ (2)$$

Where

C - Dimensionless factor

P - Internal design pressure

S - Maximum Allowable stress

E – Efficiency

W = π/4 d^{2}p

The flange design is carried out using Schneider's approach.

Thickness of flange is given by

Thickness =

$$1.1\ x\ R_m\ x\ \sqrt{\frac{3\ x\ P\ X\ L}{Strength\ of\ Flange\ x\ (1-N\ xP)x\ (Rm+L)}}$$

---------- (3)

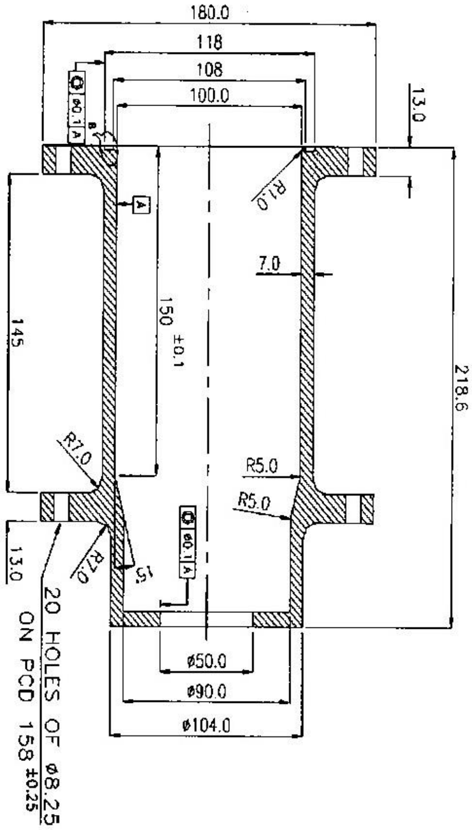

Figure 3.1: Drawing Details of Rocket Thruster

From the formulae shell thickness calculated is 6.583 mm and injector plate thickness is 14.54 mm. Considering mismatch factor we have taken shell thickness as 7.00 mm and injector plate thickness as 14.00 mm and flange thickness is taken as 13.00 mm.

IV. MATERIAL PROPERTIES

SS AISI 321A material and SS AISI 304 material are chosen for the fabrication of thruster assembly.

EN – 24 (12.9 class) material is chosen for bolts.

Since, allowable stress of SS AISI 321A material is more than that of SS AISI 304, the former one is chosen for design.

A. Mechanical Properties of SS 321A Material

Tensile strength	:	540 MPa
0.2% Yield Strength	:	210 MPa
% Elongation in 4D	:	35
Modulus of Elasticity	:	210 GPa
Poisson's Ratio	:	0.3
Density	:	7800 kg/m^3
Hardness	:	183 HB (Max)

Factor of Safety as per ASME Pressure Vessel Code:

On Yield = Y.S/1.50 σ allowable =140 MPa

On UTS = UTS/3.0 σ allowable =180 MPa

B. Mechanical Properties of EN -24 bolts (12.9 class):

Ultimate Tensile Strength	-	1200 MPa
Yield Strength (SS 304)	-	1080 MPa

Factor of Safety as per ASME Pressure Vessel Code:

On Yield = Y.S / 1.50 σ allowable = 720 MPa

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V. STATIC ANALYSIS OF ROCKET THRUSTER

The FE analysis of reaction control system thruster is carried out for maximum operating pressure of 100 bar applied radially inside the shell and 150 bar applied radially inside the area of oxidizer and fuel adaptor of injector plate. The analysis is carried out using ANSYS 12.0 software. The 3D axisymmetric model of thruster subjected to axisymmetric loads is represented in equivalent 2D form in ANSYS. The model is meshed using Quadrilateral 4 noded 42 (PLANE 42 from ANSYS library) solid elements.

A. Element description:

The element type determines the degrees of freedom and whether the element lies in the 2D – space or 3D – space. The element type considered in the analysis is plane 42.

B. PLANE 42 2-D Structural Solid Element:

PLANE 42 is used for 2-D modeling of solid structures. The element can be used either as a plane element (plane stress or plane strain) or as an axisymmetric element. The element is defined by four nodes having two degrees of freedom at each node: translations in the nodal x and y directions.

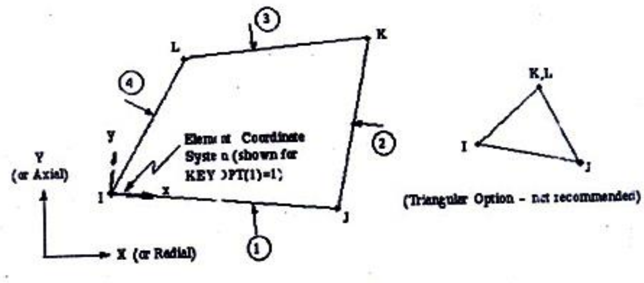

Figure 5.1: Plane 42 2-D structural Element

VI. PROBLEM DESCRIPTION

In the present work, thermo-structural analysis is carried out for two design cases of the model. In the first case, the thruster is modeled in ANSYS using Plane 42, 2-Dimensional structural solid element considering the drawings provided by DRDL, Hyderabad (shown in figure 6.1). Some modifications are considered in the second case. A groove is created on the injector plate, instead of welding the L-dome to the injector plate. A threading is provided on the injector plate and L-dome to accommodate the groove (shown in figure 6.2). Von-mises stresses are estimated for both the cases and compared.

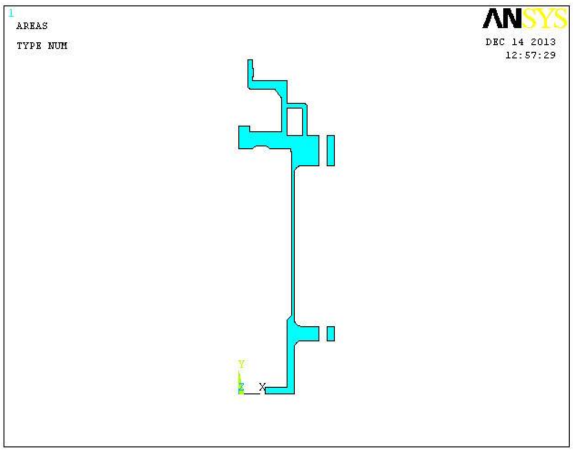

Figure 6.1: Area diagram for case 1 model

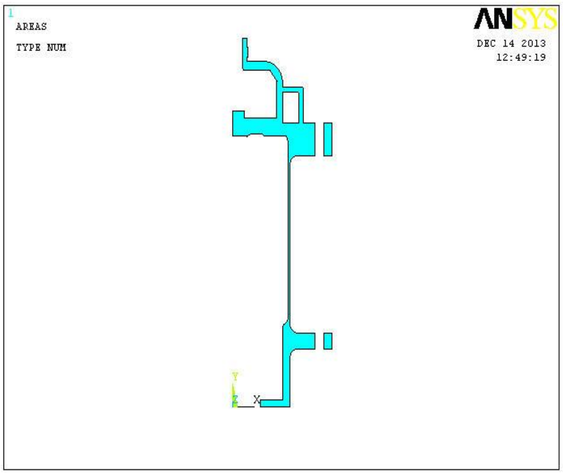

Figure 6.2: Area diagram for case 2 model

Since the modeled geometry is axi-symmetric the thruster in 3-Dimensional form is seen as below

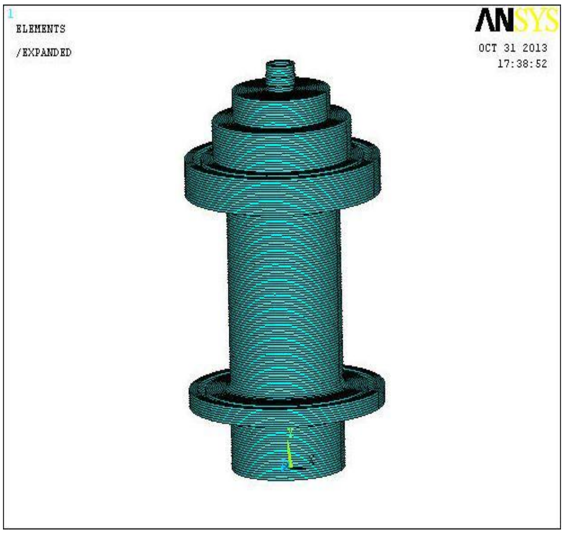

Figure 6.3: 3-D Model of Thruster for case 1

VII. STEPS CONSIDERED IN THE ANALYSIS

A. Static Analysis

The different components of thruster assembly are held together either by welding or by bolts. They are considered as single integrated part in the axisymmetric model. The axisymmetric finite element model of thruster so created greatly reduces the modeling and analysis time compared to that of an equivalent 3-D model. The fuel orifice adaptor is not modeled as it is not symmetric but the pressure developed by it is considered in the analysis. The model is meshed using Quadrilateral 4-noded 2D solid elements. It is a four noded element with two degree of freedom at each node i.e. translations in x and y directions.

B. Coupling

Coupling is done to force two or more degrees of freedom to take on the same value. In the axisymmetric analysis of thruster the equivalent area of bolt connecting the flange of shell and injector plate at the opending end is calculated and the same is considered as continous strip in the analysis.

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C. Pretension of Bolt

The bolts connecting the flange of shell and injector plate at the rear end of thruster are subjected to torque when tightened with nut. The reduced area of the bolt strip is selected and nodes within the area are subjected to the temperature of 61.74 ^{0}C. The temperature to be applied is calculated using the following formula:

Stress (σ) = 60% of Yield Strength of EN-24 Bolt

= 0.6 x 1080 = 648MPa

$$\text{Strain } (\varepsilon) = \frac{\sigma}{E} = \frac{648}{2.1 \, x \, 10^5} = 3.085 \text{ x } 10^{-3}$$

Now, Strain (ε) = Q x Δt

$$\text{i.e.} \quad \Delta t = \frac{3.085 \, x \, 10^{-3}}{5 \, x \, 10^{-5}} = 61.74 \ ^0\text{C}$$

D. Contact Analysis

The injector and flange of the shell are not welded instead held down by bolts and hence the contact is established by inserting a CONTACT12 2-Dimensional point-to-point element between the coincident nodes of flange and injector in the positive Y direction.

E. Loads Applied

In this step, we define the analysis type and analysis options, apply loads, and initiate the finite element solution. The applied loads were

a) Pressure of 100 bar applied radially inside shell and 150 bar inside Oxidizer Adaptor area and L-Dome area of injector plate.

b) The nodes of the equipment reduced area of Bolts are subjected to temperature of 61.74^{0}C in order to induce pretension in the bolts.

F. Boundary Conditions

The Rocket thruster meshed with boundary conditions is as shown in figure 6.2.

The applied boundary conditions are:

a) Holes on front flange of shell constrained in all direction.

b) Nodes of reduced area of Bolt are coupled with nodes of injector plate and flange of shell.

c) The Symmetry Boundary Condition applied on vertical line joining shell and injector of thruster in the + Y - direction.

Figure 7.1: Thruster mesh with boundary conditions

VIII. RESULTS

Analysis has been carried out and von mises stresses are estimated for two design cases. Initially thermo-structural analysis has been carried out considering the design limit load of 100 bar and temperature of 61.7 ^{o}C for two design cases and von mises stresses are estimated. Further the study on the analysis is extended to a pressure of 125 bar and temperature of 100 ^{o}C.

A. At 100 bar pressure and coupled with temperatures

i. Case 1

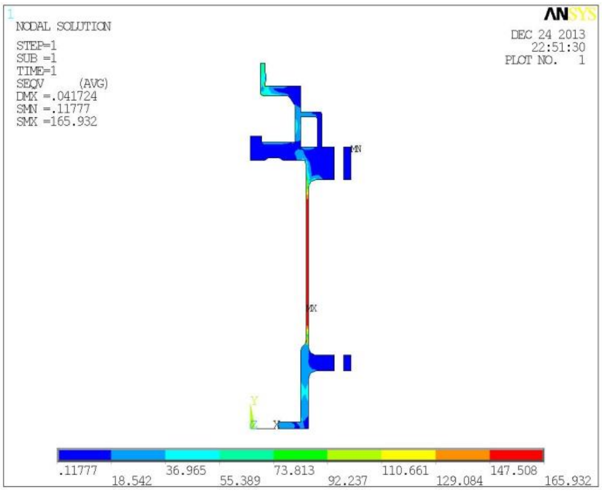

Figure 8.1: Von Mises stresses at 100 bar pressure

From the above figure it is observed that the maximum Von Mises stress in the structure of the thruster casing for case 1 at 100 bar pressure is 165.9 MPa.

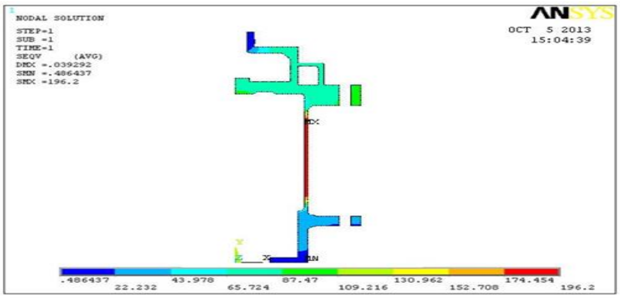

Figure 8.2: Von Mises stresses at 100 bar pressure and temp 61.7 ^{o}C

From the above figure it is observed that the maximum Von Mises stress in the structure of the thruster casing for case 1 at 100 bar pressure and temperature 61.7 ^{o}C is 196.2 MPa.

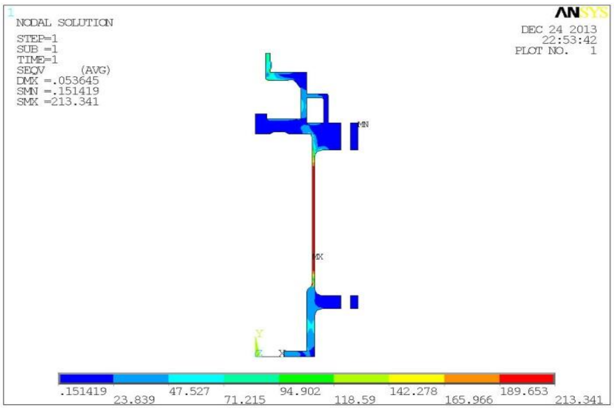

Figure 8.3: Von Mises stresses at 100 bar pressure and temp 100 ^{o}C

From the above figure it is observed that the maximum Von Mises stress in the structure of the thruster casing for case 1 at 100 bar pressure and temperature 100 ^{o}C is 213.34 MPa.

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ii. Case 2

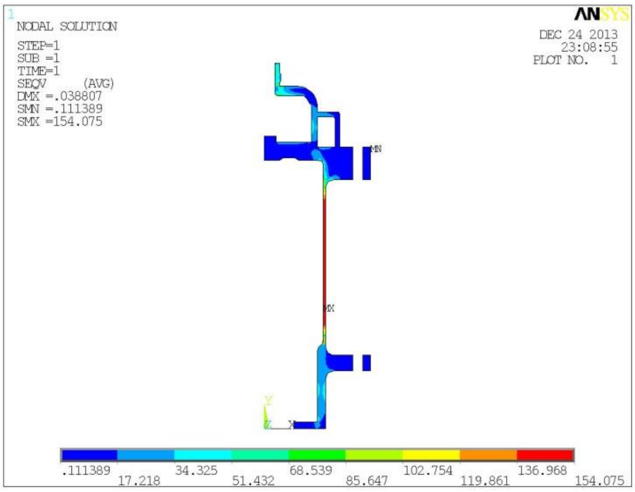

Figure 8.4: Von Mises stresses at 100 bar pressure

From the above figure it is observed that the maximum Von Mises stress in the structure of the thruster casing for case 2 at 100 bar pressure is 154.1 MPa.

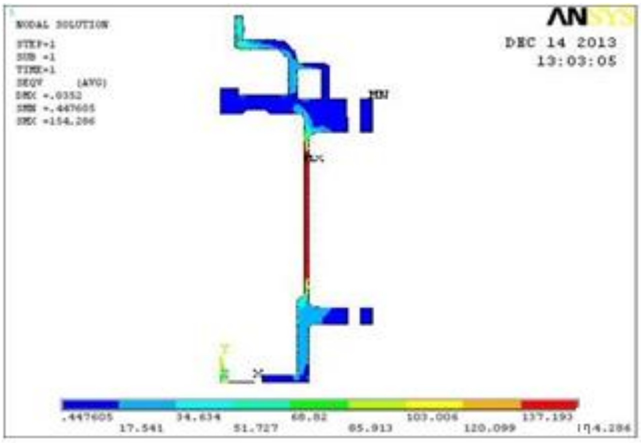

Figure 8.5: Von Mises stresses at 100 bar pressure and temp 61.7 °C

From the above figures it is observed that the maximum Von Mises stress in the structure of the thruster casing for case 2 at 100 bar pressure and temperature 61.7°C is 174.28 MPa.

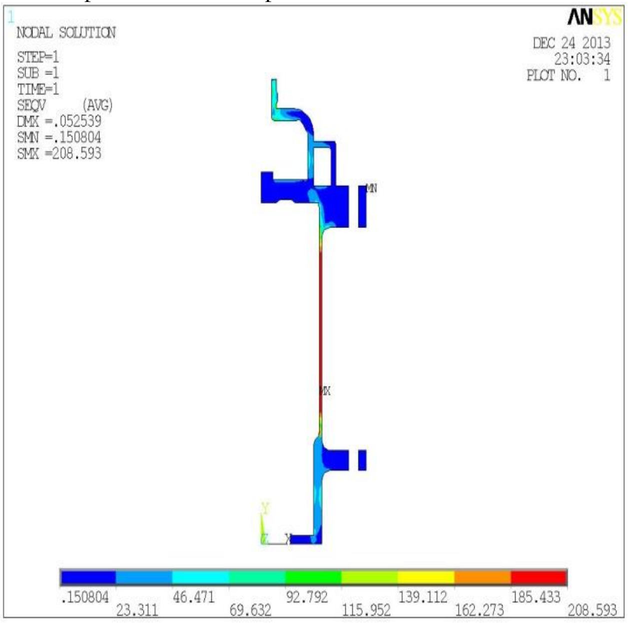

Figure 8.6: Von Mises stresses at 100 bar pressure and temp 100 °C

From the above figure it is observed that the maximum Von Mises stress in the structure of the thruster casing for case 2 at 100 bar pressure and temperature 100 °C is 208.593 MPa.

B. At 125 bar pressure and coupled with temperatures

i. Case 1

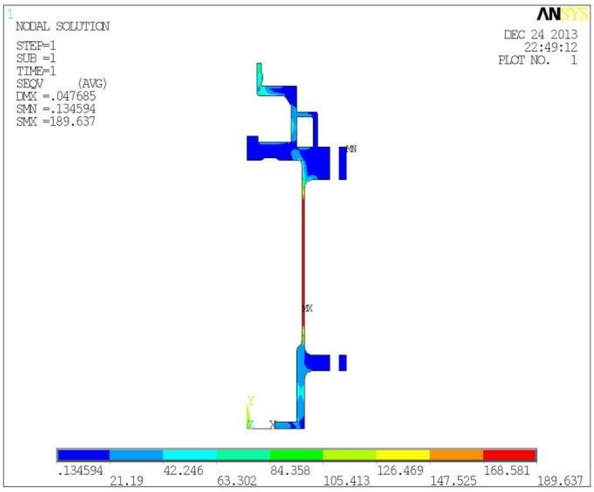

Figure 8.7: Von Mises stresses at 125 bar pressure

From the above figure it is observed that the maximum Von Mises stress in the structure of the thruster casing for case 1 at 125 bar pressure is 189.63 MPa.

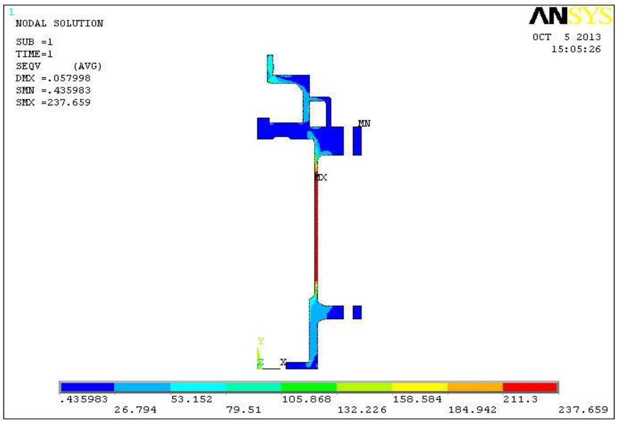

Figure 8.8: von Mises stresses at125 bar pressure and temp 61.7 °C

From the above figure it is observed that the maximum Von Mises stress in the structure of the thruster casing for case 1 at 125 bar pressure and temperature 61.7 °C is 237.659 MPa.

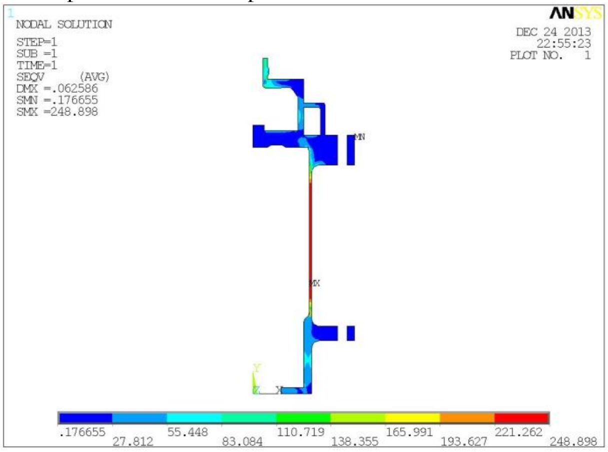

Figure 8.9: Von Mises stresses at 125 bar pressure and temp 100 °C

From the above figure it is observed that the maximum Von Mises stress in the structure of the thruster casing for case 1 at 125 bar pressure and temperature 100 °C is 248.896 MPa.

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ii. Case 2

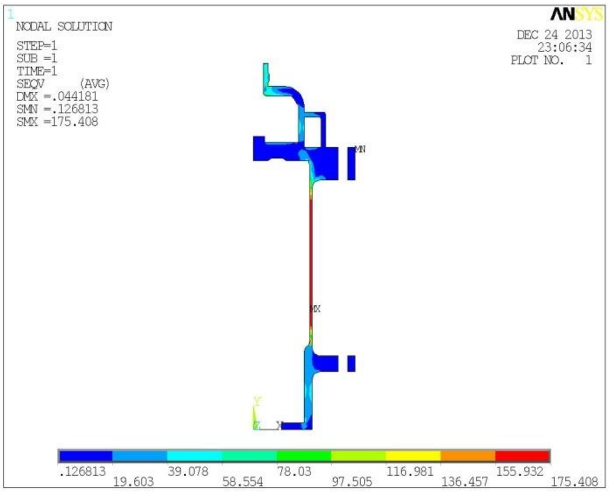


Figure 8.10: Von Mises stress at 125 bar pressure

From the above figure it is observed that the maximum Von Mises stress in the structure of the thruster casing for case 2 at 125 bar pressure is 175.408 MPa.

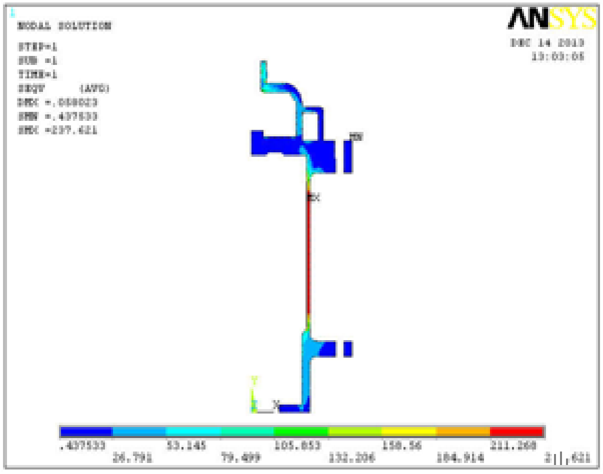


Figure 8.11: von Mises stress at125 bar pressure and temp 61.7 °C

From the above figure it is observed that the maximum Von Mises stress in the structure of the thruster casing for case 2 at 125 bar pressure and temperature 61.7 °C is 211.62 MPa.

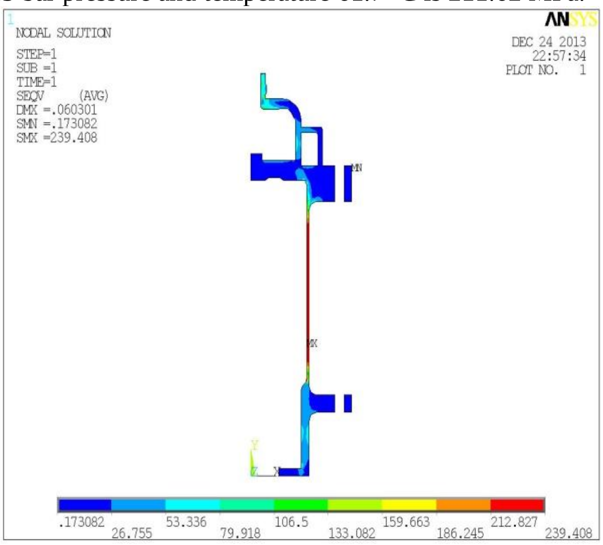


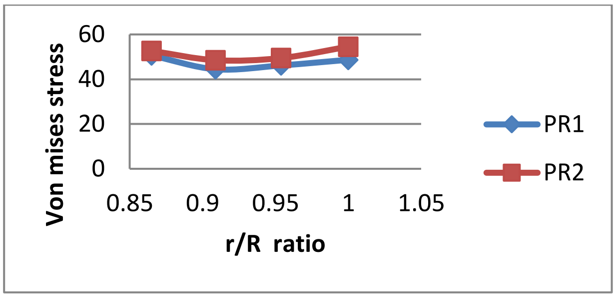
Figure 8.12: von Mises stress at 125 bar pressure and temp 100 °C

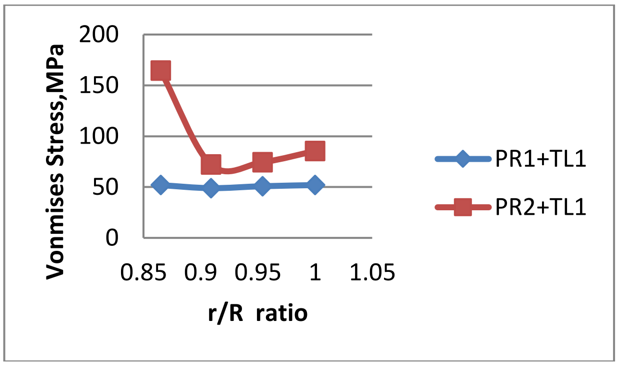
From the above figure it is observed that the maximum Von Mises stress in the structure of the thruster casing for case 2 at 125 bar pressure and 100 °C is 239.408 MPa.

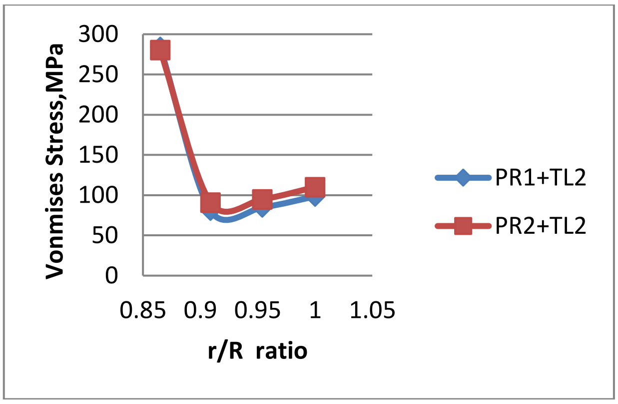
C. Discussion on Results

The variations for case 1and case 2 are seen in the following figures considering a plot drawn between r/R ratio and von mises stress. The values are taken at a section and plots are drawn. The following notations are taken for clarification. The pressures 100 bar and 125 bar are represented as PR1 and PR2 and temperatures 61.7 °C and 100 °C as TL1 and TL2.

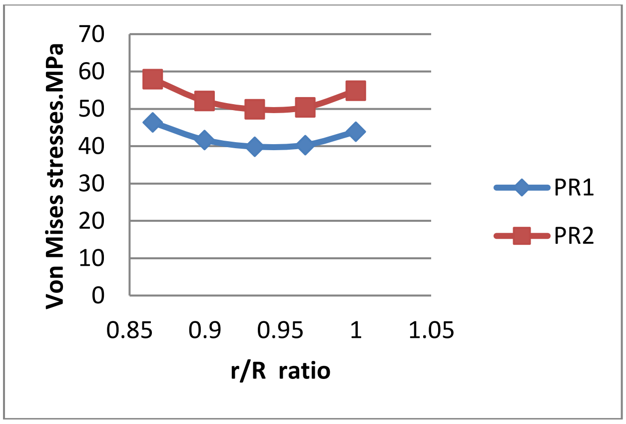
i. Case 1







ii. Case 2



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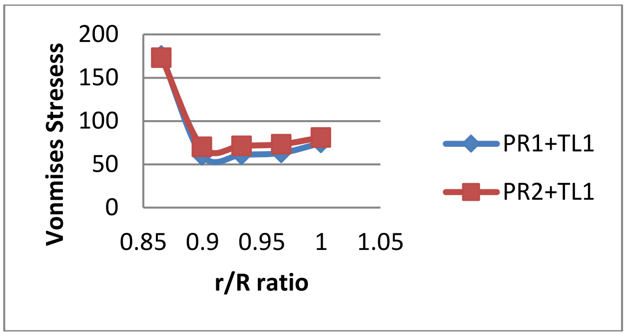

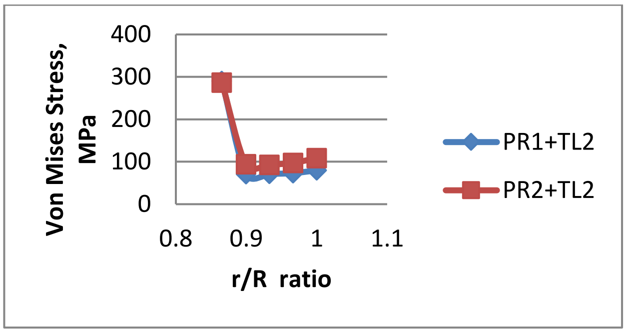

IX.CONCLUSIONS

Structural analysis is carried over the Rocket thruster system. The thruster system is analyzed for internal chamber pressures 100 bar and 125 bar, using plane 42 solid element.

The following conclusions are drawn from the present work.

- The maximum von mises stress observed in the structure of the casing when thermo-structural analysis has been carried out for pressure 100 bar and temperature 61.7 ^{o}C is 196.2 Mpa for case 1 and 174.28 MPa for case 2 which are less than the yield strength of the thruster casing material.
- The maximum von mises stress observed in the structure of the casing when thermo-structural analysis has been carried out for pressure 125 bar and temperature 61.7 ^{o}C 237.65 Mpa for case 1 and 211.62 Mpa for case 2. When the pressure is increased to 125 bar it is observed that the stresses are exceeding the design limit values.

Hence the design of the thruster casing is safe based on strength criteria. Finally from the results obtained, it is concluded that the structure is safe under given operating pressure conditions. Both designs are within safe limits but the second model is considered to be better one for the fabrication and the design easiness to minimize the weight of the Rocket Thruster due to the elimination of welding of L-dome to injector plate.

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