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Coupled Field Analysis of Nose Cone of a Re-entry Vehicle

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Abstract:

Aerodynamic heating and drag plays crucial role in the thermal stability of reentry vehicle. The design of nose cone structure demands an effective Thermal Protection System (TPS). The most difficult task in TPS design is the defining the thermo-mechanical properties of the heat-shielding material of reentry vehicles at the reentry in the atmosphere. The Conventional reentry vehicles use liners and foam materials as insulating materials in the design of TPS. The main objective of this work is to present a Coupled Field Analysis of Nose Cone of a Reentry vehicle using ultra high temperature composite materials like Hafnium diboride (HfB2) and zirconium diboride (ZrB2) as insulating materials through Finite Element Analysis approach. In this work a special attention is devoted to the modeling of composite material lay-ups and greater numerical efficiency. This work encompasses;

- *To study the effect of Thermal loads on the structure and to observe how the structure reacts because of the thermal loads.*
- *Providing exposure to various coupled field analyses.*

Keywords: *Aerodynamic heating, Reentry Vehicle, Thermal Protection System, Coupled field analysis, ANSYS.*

1. Introduction

There are basically 2 tpes of reentry vehicles exist in the field. Those are Manned Reentry Vehicles and Unmanned Reentry Vehicles. The present work is focusing on Manned Reentry Vehicles. Manned Re-Entry Vehicles are the compartments designed to support humans during their journey in the space. They must contain the basic elements that astronauts need to live like air to breathe, water to drink, and food to eat. They also have to protect the astronauts from the cold in space and space radiation. These are well insulated and contain systems to adjust the internal temperature. There must be a way for the astronauts to secure themselves so they don't get jostled around during launch or re-entry.

1.1 Gravity and Momentum

Gravity is the force that attracts bodies to one another. The Sun's gravity holds the planets in their orbits, and the planets' gravity hold their moons in orbit around them. Gravity pulls all objects down to the surface of a planet. Spacecraft launched at high speeds against the pull of gravity orbit the Earth and then fire jets to re-enter the atmosphere. Gravity does the rest of the work bringing them home. “G-force” is a term used to express how many times the usual Earth gravity force an astronaut feels upon launch and upon re-entry when the speed creates the G-force. Today's shuttle astronauts experience only a few (2-3) G's upon launch and re-entry. The Russian cosmonauts, however, experience higher G's (6-7) upon launch and re-entry. As objects fall, they pick up momentum or accelerate until they impact the surface. Planets with atmospheres will create

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friction (and heat) with the spacecraft. Spacecraft like the shuttle are designed to fly like gliders and land aerodynamically. Vehicles like the Soyuz and early NASA Mercury, Gemini and Apollo capsules used parachutes to help slow their fall. Both types of spacecraft have heat shields on their bottoms. In the Egg-astronaut activity, gravity and momentum are the major forces acting on the Vehicle.

1.2 Re-entry Motion

Returning from space, Earth's atmosphere presents a dense, fluid medium, which at orbital velocities, is not all that different from a lake's surface. Austronauts must plan to hit the atmosphere at the precise angle and speed for a safe landing. If they hit too steeply or too fast, they risk making a big "splash," which would mean a fiery end. If their impact is too shallow, they may literally skip off the atmosphere and back into the cold of space. This subtle dance between fire and ice is the science of atmospheric re-entry.

All space-mission planning begins with a set of requirements we must meet to achieve mission objectives. The re-entry phase of a mission is no different. We must delicately balance three, often competing, requirements

- ✓ Deceleration
- ✓ Heating
- ✓ Accuracy of landing or impact

As you can see from all these constraints, a re-entry vehicle must walk a tightrope between being squashed and skipping out, between fire and ice, and between hitting and missing the target. This tightrope is actually a three-dimensional "*re-entry corridor*" through which a re-entry vehicle must pass to avoid skipping out or burning up. The size of the corridor depends on the three competing constraints— deceleration, heating, and accuracy. The re-entry corridor is a narrow region in space that a re-entering vehicle must fly through. If the vehicle strays above the corridor, it may skip out. If it stays below the corridor, it may burn up. *"Re-entry flight-path angle"*, which is the angle between the local horizontal and the velocity vector. To truly understand the motion of a re-entering Shuttle, we have to start by listing what forces might affect it.

1.3 Vehicle Shape

The re-entry vehicle's size and shape help determine the ballistic coefficient (BC) and the amount of lift it will generate. The hardest component of BC to determine for re-entry vehicles is the drag coefficient, C_D, which depends mainly on the vehicle's shape. At low speeds, we could just stick a model of the vehicle in a wind tunnel and take specific measurements to determine C_D. But at re-entry speeds approaching 25 times the speed of sound, wind tunnel testing isn't practical because no tunnels work at those speeds. Instead, we must create mathematical models of this hypersonic flow to find C_D. The most accurate of these models requires us to use high-speed computers to solve the problem. This approach is now a specialized area of aerospace engineering known as *computational fluid dynamics (CFD).* A simulation of the nose cone of a reentry vehicle in flight in air during the reentry is performed solely for the purpose of estimating the structural and thermal stiffness of the nosecone. Simulation is done with the help of classical ANSYS. This problem includes the testing of the combination of three composite materials whose properties are applied steadily to the nose cone.

2. Literature Review

The studies for nose cone of Vehicle and the materials chosen because the experimental results are available in various aspects with different temperature ranges with material selection. To understand the nose cone interaction problem, we need to analyze both structural and thermal analysis in ANSYS.

Agosh M C[1] in his work "Aerodynamic And Heat Transfer Analysis Over Spherical Blunt Cone" has presented the computational simulations that were carried out on a spherical blunt body to determine the aero thermodynamic coefficients at various hypersonic mach numbers. The sea level conditions were assumed for the computational simulations. Computations were validated through a simulation of flow field around spherical blunt body at Mach numbers 6, 7 and 8.

N. S. Babu and K. J. Rao[2] in their work "Analysis Of Blunt Nose Cone With Ultra High Temperature Ceramic Composite TPS Materials" has presented the Aerodynamic drag and heating are the crucial in the thermal stability of hypersonic vehicles at various speeds. The latest developments in the design of nose cone structure demands an effective Thermal Protection System (TPS) meets the need of the space research technology. In this research a typical nose cone with different Ultra High Temperature (UHT) ceramic composite TPS materials like Hafnium diboride (HfB_2) and zirconium diboride (ZrB_2) is analysed and compared for its effective protection against transfer of heat into the structure. A naval model is designed for from the concepts of blunt nose cone and analysed with the commercial software.

J. Muylaert et al. [3] in their work "Aerothermodynamics Analysis Of Space Vehicle Phenomena" has presented aerothermodynamics is a key technology for the design and optimisation of space vehicles because it provides the necessary databases for, example, the choice of trajectory, guidance, Navigation and control, as well as for the thermal-protection and propulsion systems. This article presents its current capabilities with respect to flow Phenomena. Examples are presented of external flows past re-entry vehicle demonstrators and launchers. Internal flow problems associated with propulsion and the interactions with external flow are also presented.

Jack V. Snyder et al[4] in their work "Experimental Near Space Free Fall Testing Systems" has presented The High Altitude Balloon program (WSU HiBal) is making headway toward completion of systems that facilitate near space free fall experimentation. Development of these flight capabilities is a pioneering mission for the WSU program and will add another dimension to HiBal experimentation. Results from this research may provide cost effective and practical solutions for stability testing of re-entry vehicles such as ballutes. Several launches have been performed for development and testing of electrical, mechanical, and computer systems associated with free fall experimentation and high altitude ballooning. Improved launch procedures and pre-flight system testing has given WSU the ability to launch balloon payload systems in the harshest Ohio weather. Such program developments provide opportunities for year round flight experiments.

2.1 Inference from the Literature Survey

After going through a lot of published work regarding the re-entry vehicles, it can be understood that these re-

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entry vehicles are used for the emergency return of personnel from the International Space Station. For injured occupants, or those with emergency medical conditions, a re-entry environment would be necessary. This can only be met by using a relatively conventional design employing leading-edge bluntness and a passive thermal-protection system. Many experimental results from the previously published thesis have been referred and understood that Coupled - Field Analysis is one of the kind of analysis which is responsible for countless useful effects in engineering. This project involves the Coupled - Field Analysis performing both thermal, structural analysis and taking gravitational effects in to consideration. The completion of literature survey, helps us to understand the phenomena and mechanism of Coupled - Field Analysis and get a fundamental knowledge and information for the analysis of Coupled - Field Analysis problems occurring on the various structures, and mainly on the blunt nose cone of the Vehicle from the previously published thesis.

Coupled - Field Analysis has a critical impact on the design and performance of any structure these days. The basic idea started with the basic idea of railway tracks being elongated at the time of summer. If the summer heat is making such difference in structures, then the re-entry vehicles which will get heated because of "Aerodynamic heating." These vehicles which are acted upon by "g" force, and thermal forces may show some adverse effects on the passengers who are inside the Vehicle or may lead to a complete mission failure. One such disaster is of Kalpana Chawla's "Space shuttle Columbia Disaster." The class dealing with problems where more than one physical effect is involved comprises the so-called "multi-physics problems", among the most important of which is Coupled - Field Analysis, challenging with respect to both modeling and computational issues. Coupling here is a very tough task to be accomplished i.e. coupling of thermal results with structural solver and assigning gravity loads. A blunt nose from on the references is considered and some modifications are done to the design and additional gravity loads are applied to see the effects that are levied on the Reentry Vehicle.

3. Coupled Field Analysis

To improve the accuracy and efficiency of the finite element method, development of an approach called integrated thermal-structural analysis was initiated. The goals of the integrated approach are to: (1) provide thermal elements which predict detailed temperature distributions accurately, (2) provide structural elements with improved displacement and stress distributions which are fully compatible with the thermal elements, and (3) integrate the thermal loads with the structural analysis to further improve the accuracy of displacements and stresses.

The goals of the integrated approach require developing new thermal and structural finite elements that can provide higher accuracy and efficiency than conventional finite elements. Displacements and stresses based on the new thermal elements were improved because more accurate thermal loads were provided to the structural finite element analysis. Another task of the integrated approach is to develop new structural elements capable of providing improved displacement and stress distributions. By integrating these new structural elements with the new thermal elements developed previously, better thermal-structural solution accuracy can be obtained.

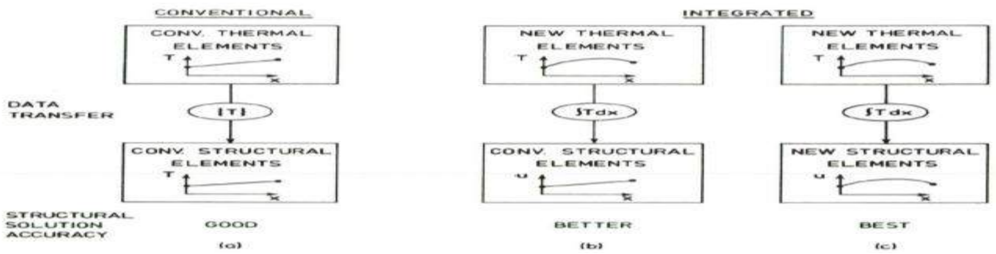

Fig. 1 Method of improving thermal – structural solution accuracy

4. Finite Element Modeling using Ansys Model of the Nose Cone

The spline model is designed in CATIAV5 and after that the spline model will be imported to ANSYS after importing the spline model the new co-ordinate system should be created for the sake of meshing we are going to use a new co-ordinate system (11-cordinate system) which was created by using the three KP (key points). Because of which the meshing and lay-ups of material will become easier.

Table: 1. Material properties

Material/ Properties	E(N/mm^2)	1/m	P (kg/mm^3)	α (^{0}k^{-1})	K (W/mm-K)
Carbon Epoxy composite	1.81e5	0.36	1.7e-6	2e-6	7e-3
Hafnium diboride (Hfb2)	0.75e5	0.37	10.5e-6	7.6e-6	62e-3
Zirconium diboride (Zrb2)	4.2e5	0.34	6.085e-6	8.3e-6	70e-3

The profile is designed in CATIAV5 software by taking the reference dimensions the mesh model of the nose cone where we did the mapped mesh for the nose cone

4.1 Applied Boundary Conditions

Temperature loads are applied, minimum temperature as 298K inner side of the nose cone the maximum temperature as 2798 K outer side of the nose cone .

Gravity: The inertial force should be applied in the y-direction value is -30g(g-9.81n/mm) . This force is given because the Vehicle will be re-entering into the earth's atmosphere without any additional propulsion system

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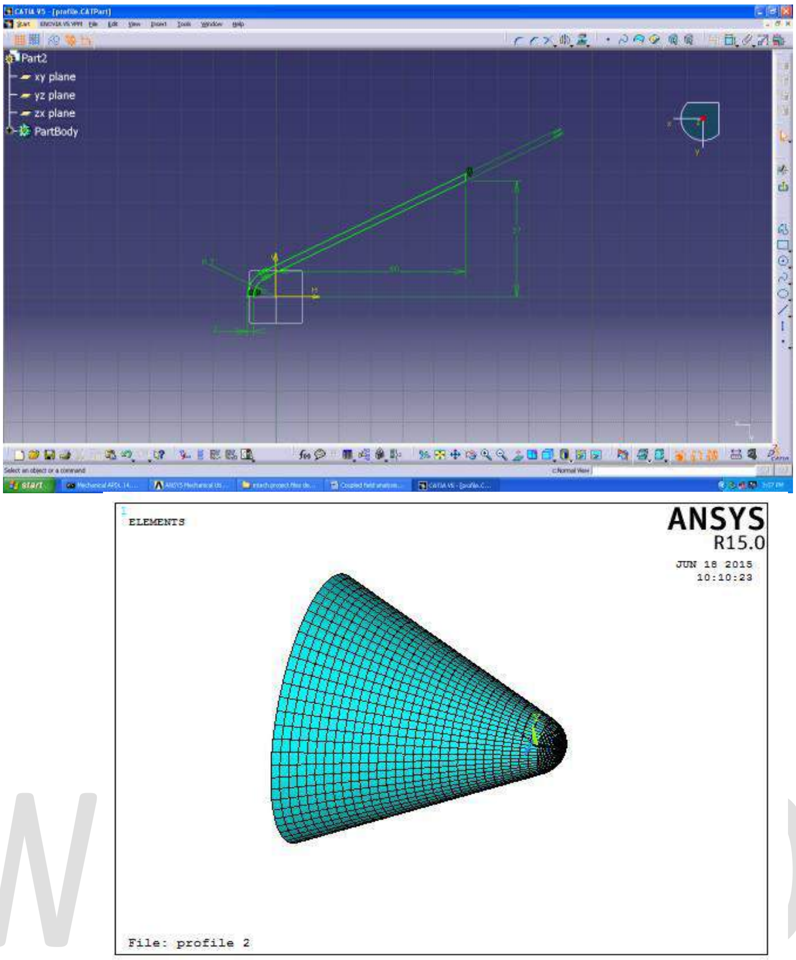

Fig.2 Wire frame model and Meshed model 3d

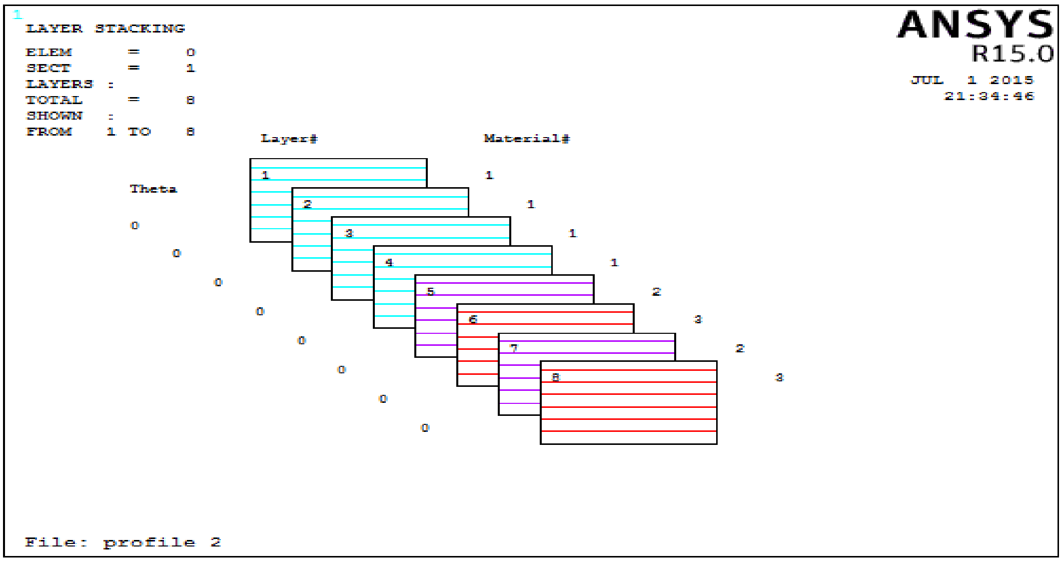

Fig. 3. Shell Lay-Up’s

Table:2. Lay-up application for material

S. No	Thickness	Material-Id
1	0.25	1
2	0.25	1
3	0.25	1
4	0.25	1
5	0.25	2
6	0.25	3
7	0.25	2
8	0.25	3

5. Results and Discussion

5.1 Von-Mises Stress

Von-mises stress: Von Mises stress is widely used by the designers to check whether their design will withstand a given load condition. In this lecture we will understand Von Mises stress in a logical way.

Use of Von-Mises stress: Von mises stress is considered to be a safe haven for the design engineer’s .Using this information an engineer can say his design will fail, if the maximum value of Von Mises stress induced in the material is more than strength of the material. It works well for most of the cases, especially when the material is ductile in nature. In coming sections we will have a logical understanding of Von Mises stress and why it is used.

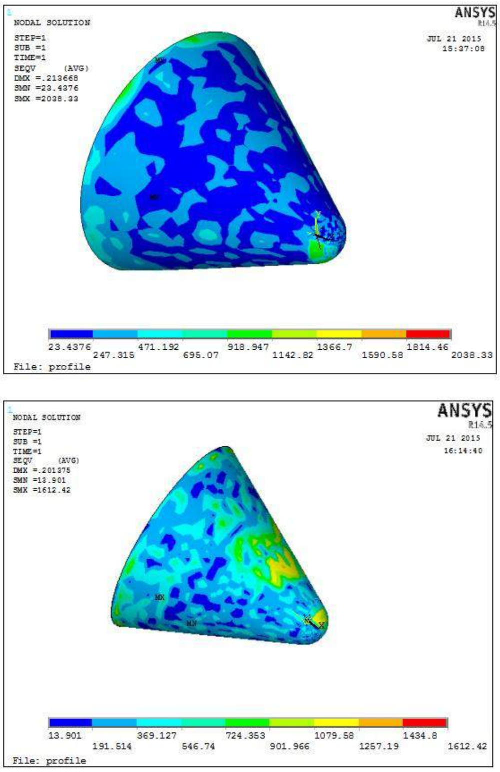

Fig. 4. Von-Mises Stress with and without gravity

The above reactions are the von-mises stress on the nose cone structure when the gravity is applied here the von mises stress is distributed on the whole body of the nose cone structure the failure section will be less affected in red colour the whole body is protected i.e, the forces applied on the nose cone structure will be distributed failure area will be less on the nose cone structure. When the gravity is not applied on the nose cone structure the legend table shows the comparison between gravity applied and not applied on the nose cone structure with gravity the von mises stress blue color value- 23.4376, without gravity – 13.901 by applying gravity the von mises stress is stable on the nose cone structure.

5.2 Displacement Rections

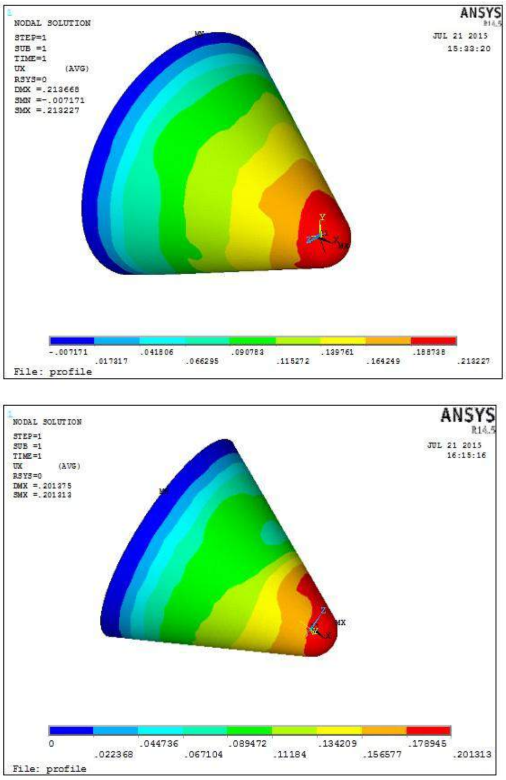

Fig.5. Displacement X-direction with and without gravity

The above reaction is displacement through X-direction when gravity is applied on the nose cone structure here we can observe clearly the red color is more affected area on the front side of the nose cone because when the Vehicle is returning to the atmosphere the front side will be more affected, blue color is the less affected area on the nose cone structure observing the nose cone the blue color is at the end surface of the structure. The legend table gives more information of the affected forces on the nose cone structure.

Displacement through X-direction when gravity is not applied on the nose cone structure here we can observe clearly the red color is more affected area on the front side of the nose cone because when the Vehicle is returning to the atmosphere the front side will be more affected, blue color is the less affected area on the nose cone structure observing the nose cone the blue color is at the end surface of the structure. By comparing displacement with gravity and without gravity displacement at X-direction will be varied. Legend table shows the difference when the gravity is applied the reaction of displacement-0.213227, without gravity the displacement reaction-0.201313.

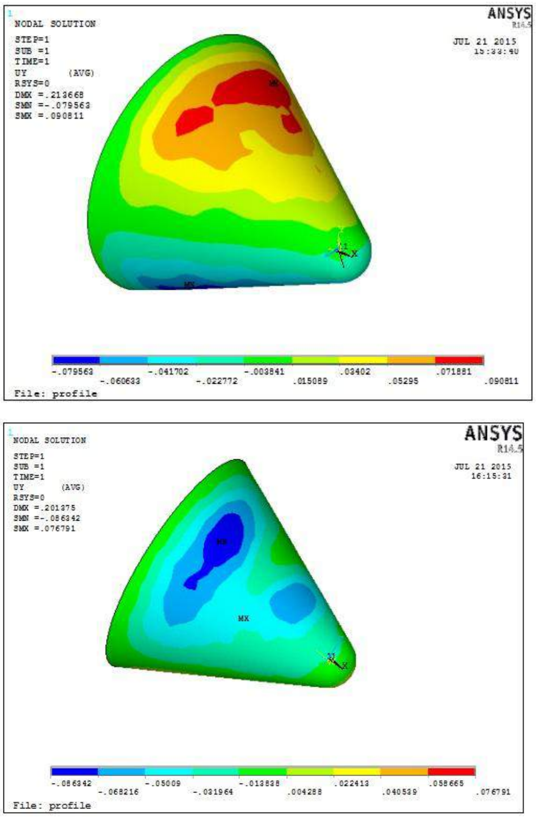

Fig.6. Displacement Y-direction with and without gravity

The above reaction is displacement through Y-direction when gravity is applied on the nose cone structure, here we can observe clearly the red color is more affected area on the upper surface of the nose cone because when the Vehicle is returning to the atmosphere the upper surface will be more affected because the direction is through Y, blue color is the less affected area at the bottom surface of nose cone structure by observing blue color is at the bottom surface of the structure. The legend table gives more information of the affected forces on the nose cone structure.

Displacement through Y-direction when gravity is not applied on the nose cone structure here we can observe the blue color means less affected area on the upper surface of the nose cone because when the Vehicle is returning to the atmosphere the right surface will be more affected because it is in the y direction, red color is more affected area on the nose cone structure observing the nose cone the at the right surface of the structure. By comparing displacement reactions with gravity and without gravity displacement at Y-direction will be varied. Legend table shows the difference when the gravity is applied the reaction of displacement-.090811, without gravity the displacement reaction-.076791.

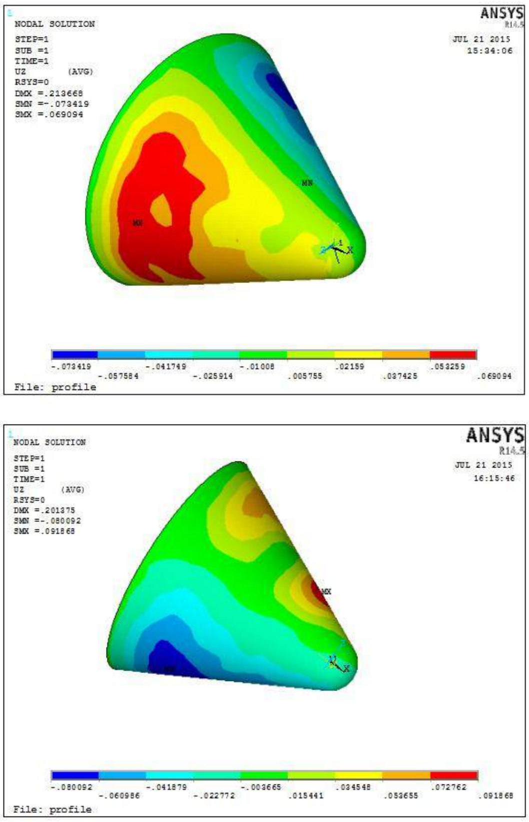

Fig.7. Displacement Z-direction with and without gravity

The above reaction is displacement through Z-direction when gravity is applied on the nose cone structure, here we can observe clearly the red color is more affected area on the left side of the nose cone because when the Vehicle is returning to the atmosphere the left side will be more affected because the direction is through Z, blue color is the less affected area at the bottom right side of nose cone structure by observing blue color is at the right side of the nose cone structure. The legend table gives more information of the affected forces on the nose cone structure.

Displacement through Z-direction when gravity is not applied on the nose cone structure here we can observe the blue color means less affected area on the bottom surface of the nose cone because when the Vehicle is returning to the atmosphere the bottom surface will be less affected because it is travelling through Z direction, red color is more affected area on the nose cone structure observing the nose cone the at the upper surface of the structure. By comparing displacement reactions with gravity and without gravity displacement at Z-direction will be varied. Legend table shows the difference when the gravity is applied the reaction of displacement- .069094, without gravity the displacement reaction-.091868.

5.3 Nodal Temperatures

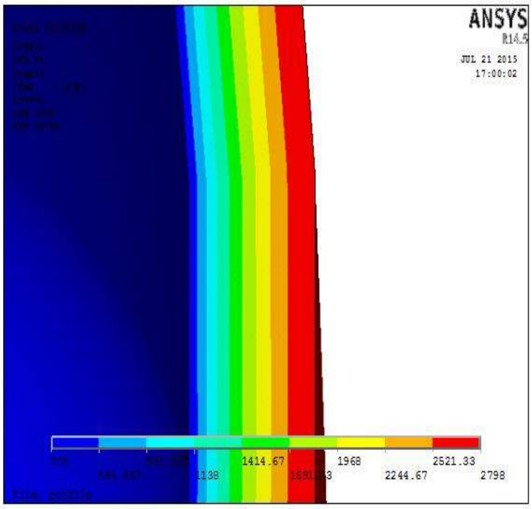

Fig.8. Nodal Temperatures

The above figure shows the nodal temperature of the nose cone. The minimum temperature at 298K and maximum temperature at 2798K. The red color shows the high temperature area from 2798 - 2520.22K. The blue color shows the minimum temperature area from 575.778 - 298K shown from the legend table i.e.., inner surface of the nose cone where the human can survive and the equipment of the nose cone the decrement from red to blue shown clearly where the temperature decrement the orange color shows 2520.22 - 2242.44K

Table: 3. Comparison of Results Between With Gravity and Without Gravity

NAME	WITH GRAVITY	WITH OUT GRAVITY
Displacement		
Vector Sum	0.21368	0.20135
X-Direction	0.21327	0.20113
Y-Direction	0.09011	0.07691
Z-Direction	0.06994	0.09168
Stress		
X -Direction	1760.35	1348.16
Y-Direction	1394.64	1255.22
Z-Direction	1801.25	1313.52
Von-moises stress	2037.33	1642.12

6. Conclusion

The desertation work concludes that the nose cone thermal and structural analysis observed the deformed and undeformed shape values are minimum, the stresses in X, Y and Z directions varied in the correct range. The shear stresses in XY, YZ and XZ planes varied in the correct range, the body temperature also varied from the outer surface to the inner surface of the nose cone i.e., maximum to the minimum, but when we compare to the von mises stresses the failure rate is more to decrease that the thickness of the outer surface of the cone can be increased then the failure rate can be decreased.

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