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Design and analysis of rocket nozzle

R. Harikrishnan [a], Bhaskara Rao Lokavarapu [b,*]

[a] *Cognizant Technology Solutions, Trivendrum, Kerala, India*
[b] *School of Mechanical Engineering, Vellore Institute of Technology, Chennai Campus, Vandalur-Kelambakkam Road, Chennai 600127, Tamil Nadu, India*

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A B S T R A C T

This paper is about the design and analysis of two different rocket nozzle configurations. First configuration is without any fillets and curved surfaces and second configuration is with fillets and curved surfaces. Second configuration is used since stress concentration will be more at the corners if we don't have an optimized geometry having suitable fillets at appropriate places. Radiuses of fillets are chosen by previous studies conducted by academicians and design scientists for optimized configurations which give less overall induced stress values and hence more life. Initial configuration and Optimized configuration were drawn in ANSYS Mechanical APDL 14.5 and coupled element Quad 8 node 223 was selected for analysis. Material selected was Ti6Al4V (Grade 5). Quadrilateral mapped meshing was done and suitable boundary conditions were applied with the help of AXIMER 1.0 software. Different plots were obtained for Degrees of Freedom solution, Stress, Thermal Flux, Thermal Gradient and Total Thermal and Mechanical Strains for the two configurations. The degrees of freedom solution is calculated for all active degrees of freedom in the model, which are determined by the union of all degrees of freedom labels associated with all the active element types. It can be controlled and in this case, it would give the total number of degrees of freedom in every element of the model. Compared the two configurations and explained why the second configuration is better than the first.

1. Introduction

A rocket engine is the only possible way of propulsion to the outer space. Rocket engines are a class of engines called reaction engines that uses thrust for propulsion according to newton's third law of motion. A rocket engine nozzle is initially converging, pinched in the middle called throat and then diverging. Hence, it is called a converging–diverging nozzle. Fig. 1 shows the Mach number distribution along a nozzle with appropriate temperature and pressure variation.

Ideally, a Mach number of 1 should be obtained at the throat but it can never occur due to various property variations. Nozzle should be designed so as to obtain Mach 1 at throat since then the efficiency of rocket will be high. Flow through the nozzle will be initially subsonic at converging region, reaches sonic around throat and exits through divergent section in supersonic speeds. Other design parameters to be kept in mind are sharpness at exit and angle of narrowing down at the throat. This minimizes the chance of separation and oblique shock at exit. The project has not lightly ignored the aspects but taken the things into due consideration and designed a nozzle that meet the above prescribed requirements and analyzed using ANSYS.

The analysis of rocket nozzles is mostly carried out in FLUENT for obtaining pressure distribution, Mach number variation and also to simulate propellant flow. Here, analysis is carried out in ANSYS Mechanical APDL 14.5 to obtain deformation, stresses and various thermal parameters. The analysis performed is coupled analysis i.e. both thermal and structural effects are considered. Normally, only one or the other would be considered. Software called AXIMER1.0 is used to obtain the boundary conditions and various sources were searched to obtain force, temperature, pressure distributions in nozzle. Property differences like stress concentration, deformation distribution due to usage of fillets at throat area and having a smooth contoured diverging section are analyzed.

* Corresponding author.
E-mail address: bhaskarbabu_20@yahoo.com (B.R. Lokavarapu).

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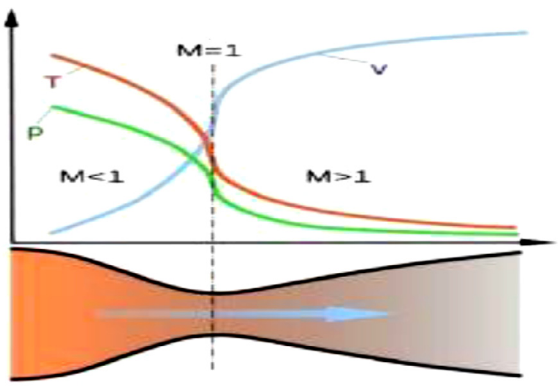

Fig. 1. Mach number distribution.

2. Literature review

For different types of mesh, different contours of nozzle like Pressure velocity, Skew angle, Mach Number etc. were calculated in ANSYS Fluent by Guven [1]. For a converging-diverging nozzle, exit diameter plays a crucial role in its performance as observed by Arjun et al., [2]. Design and structural analysis for solid rocket motor casing is carried out by Dinesh et al., [3] considering it as a pressure vessel to reduce the complications. Stephen Scampoli [4] implies that there are two ways of solving a coupled field problem in ANSYS. First is to use ANSYS Multi-field solver which does sequential iteration till solution converges. Second is to use a directly coupled-field element that solve in a single solution pass. ANSYS 22x elements allow us to solve coupled-field problems by blowing single FEM model with appropriate coupled-physics options in the element itself. Boyer [5] and Bonney and Yamane [6] and Yves [7] had proposed that due to excellent strength to weight ratio and high corrosion resistance, titanium alloys are perfect for the manufacture of nozzles let alone any aerospace parts. There are mainly α alloys, α-β alloys and β alloys depending on composition of alloy and resultant predominant room temperature constituent phase. A type of α-β alloy is Ti6AL4V which has excellent weldability and an overall good combination of properties. Starting point of a quadrilateral mesh is a triangular mesh. By combining two triangular mesh elements by a carefully controlled process, a quadrilateral mesh element is obtained. Node spacing which gets along with desired element size distribution can be obtained easily. Lau and Lee [8] observed that quality of mesh can be easily improved by a variety of mesh modification and refinement techniques. Irwin [9] had proposed that length of the duct and initial thrust are the primary functions of duct thrust in nozzles like bell-mouthed nozzle. Other than the fact that it affects initial thrust slightly, nozzle conditions and chamber pressure have no other significant effects. There are cases of rocket nozzle design which are studied by David [10] having highly efficient designs by incorporating effects like ejector effect. Ostlund [11] has proposed that there are problems with side loads and flow separation in a nozzle that severely limits the design of nozzle. Scaling laws are designed to tackle a few of these problems. Nobuyuki et al., [12] have proposed another phenomenon which is over pressure which starts with shock wave, imposes high pressure load on the nozzle. This pressure combined with vortex ring formation makes the forces acting on the nozzle asymmetric. Vipul et al., [13] have proposed that temperature profile can also be predicted using some techniques which can give velocity at exit of nozzle. John et al., [14] also observed that high heat fluxes at certain regions suggest that an effective cooling technique has to be developed to minimize this. Gerald et al., [15] have also observed a significant performance gains by adopting exhaust flow to ambient pressure. Significant payload carrying capacity increase can also be seen. Zhu et al., [16] has observed that systematic design model of the SRM with a finocyl grain can determine uncertainty relationships between parameters and system performance. Dito and Hendra [17] has observed the comparison of the thermal load contribution due to convection and radiation where convection has a dominant portion.

Based on the literature survey, it has been observed that there is no much research on the effect of fillets in different parameters of a rocket nozzle which is what exactly addressed in this paper. It plays an important role in the design of the nozzle as cost can be brought down with proper implementation of the fillets.

3. Methodology for case without fillets and arcs

3.1. Design

A. Initial design of the nozzle is shown below. It doesn't consist of any fillets or curves. Design is modelled in ANSYS as a 2D geometry by creating keypoints and lines through these keypoints. This geometry is divided into 3. This is between two corner points for ease of analysis and maximum symmetric distribution. Area is created separately in these 3 divisions using ANSYS Mechanical APDL [18] as shown in Fig. 2 after creating the geometry.

3.2. Preferences & element type

Preferences are set to 'Structural & Thermal' since we are doing coupled analysis to determine structural property changes considering thermal effects. Element type is selected as 'Quad 8 node 223′ also known as 'Plane 223′ since this element has Degrees Of Freedom of both displacement and temperature. Plane 13 is not selected since it is a 4 noded element and more accuracy is desired. In the options tab of the element, K_3 (element behavior) is made axisymmetric since nozzle is axisymmetric and K_9 (Thermoelastic damping) is suppressed to nullify its effect of giving structural nonlinearity. All other K values are unchanged.

3.3. Material model

Material properties were entered for *Ti6Al4V (Grade 5).* It's shown in Table 1. This material is chosen because it is mainly used in construction of Rocket Nozzles. It is a high-strength alloy and also has high tolerance to variations of temperature.

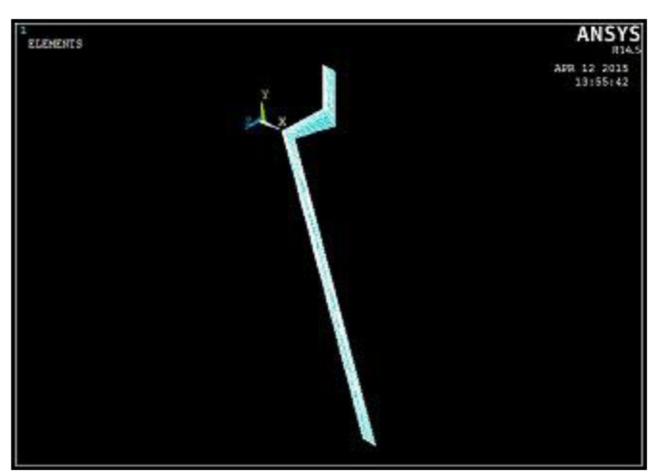

Fig. 2. Geometry of the nozzle.

Table 1
Material Properties of Ti6Al4V (Grade 5).

SL NO:	PROPERTY	VALUE
1	Density	4.43e-6 kg/mm^3
2	Specific heat capacity	0.5263e3 J/kg°C
3	Young's modulus	113800 N/mm^2
4	Poisson's ratio	0.342
5	Thermal conductivity	6.7e-3 W/mmK
6	Coefficient of thermal expansion (CTE) @ 20°	8.6e-6 mm/mm°C
7	CTE @ 250°	9.2e-6 mm/mm°C
8	CTE @ 500°	9.7e-6 mm/mm°C

3.4. Meshing

First, every line was divided into 6 divisions for the purpose of easy mapped meshing. Then, quadrilateral mapped meshing was done for obtaining uniform mesh as shown in Fig. 3.

Next, selected the elements at the inside surface and refined it to the second degree for obtaining more accurate results since inside surface is our focus area as shown in Fig. 4.Fig. 5.

3.5. Boundary conditions

Displacement at top surface was constrained in vertical direction. Also, force in vertical direction is applied at vertical direction at inner-bottom part of nozzle. Force should be acting upwards and is given by Thrust force (130 N)/number of nodes and is applied equally on each node. Pressure of 0.4 N/mm^2 is applied at inner-top part of nozzle. Pressure of 0.016 N/mm^2 is applied at constrained top surface. Thermal convection load of 5.11e-8 W/mm^2°C at bulk temperature of 24 °C is applied at outer surface and 1.113e-6 W/mm^2°C at 1200 °C is applied at inner surface. Boundary values are obtained by software called AXIMER 1.0 where if we enter a thrust load value (130 N), boundary conditions are obtained. It automatically calculates properties like thermal convection load using its inbuilt formulas under different conditions. This software also contains standard atmosphere tables and charts which it uses to calculate various boundary values.

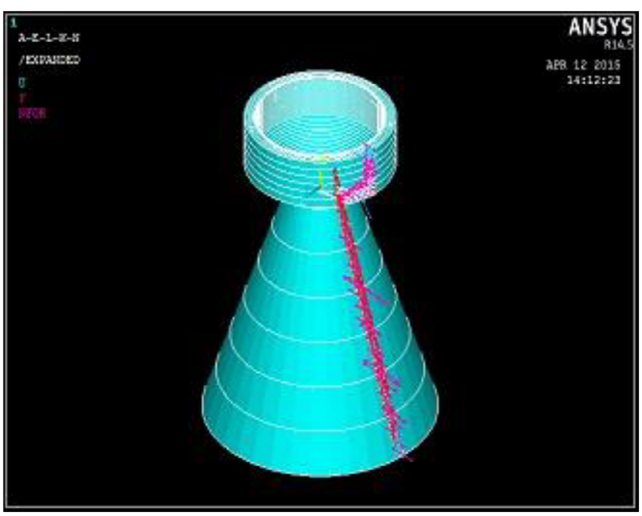

Fig. 3. After meshing.

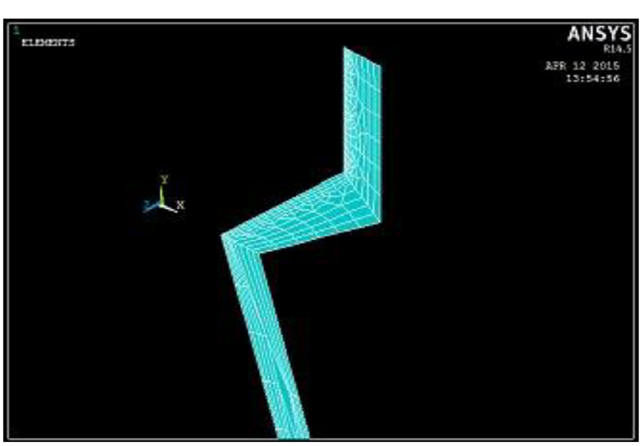

Fig. 4. After refinement.

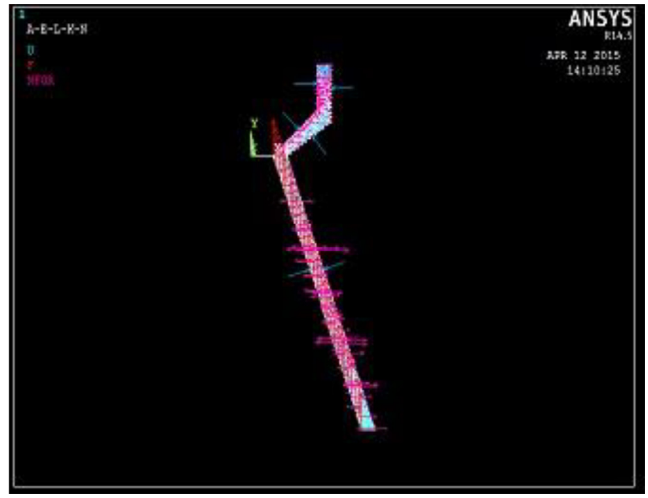

Fig. 5. After applying boundary conditions.

3.6. Solution

Solution is done for current load step and results are obtained which needs to be interpreted clearly.

3.7. Methodology for case with fillets and arcs

Same procedure is done on real geometry with fillets and arcs. Results obtained are compared with the initial obtained results. Following are Figs. 6–9 from Design to Boundary Conditions.

Fig. 6. Geometry after division of area.

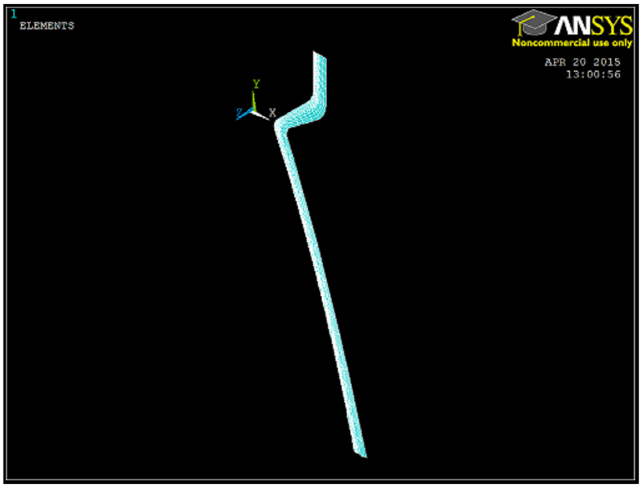

Fig. 7. After meshing and refinement.

Fig. 8. After refinement (Magnified).

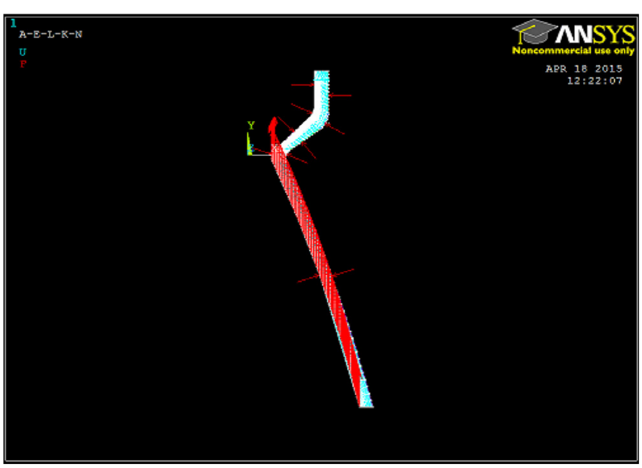

Fig. 9. After applying boundary conditions.

4. Results for case without fillets and arcs

Various results are obtained (Table 2) and some of it are interpreted and compared between the two cases.

Table 2
Difference in various results due to fillets.

Property	Nozzle without arcs and fillets	Nozzle with arcs and fillets
Deformation	1.8696 mm	1.872 mm
Stress	Max: 4.37 N/mm^2 Min: 0.011 N/mm^2	Max: 2.17 N/mm^2 Min:0.0025 N/mm^2
DOF solution	Min: 0.33 mm Max: 1.87 mm	Min: 0.3316 mm Max: 1.87 mm
Thermal gradient	Min: 0.0085 °C/mm Max: 0.026 °C/mm	Min: 0.0085 °C/mm Max: 0.026 °C/mm
Thermal flux	Min: 0.57e-4 W Max: 0.177e-3 W	Min: 0.57e-4 W Max: 0.17e-3 W
Total thermal and mechanical strain	Min: 0.12e-6 Max: 0.39e-4	Min: 0.312e-7 Max: 0.276e-4

4.1. Deformation

Deformation value is observed to be 1.869 mm which is very small. It shows that deformation is not a big factor in design of rocket nozzles even if we give straight edges. Fig. 10 shows the deformation.

4.2. Stress

Tensile Stress value is large at sharp corners. Everywhere else it's small. Tensile stress is induced due to support provided at top of nozzle surface which acts as payload of rocket. Compressive stresses are also induced but they are found to be negligible and don't cause failure. Mathematical analysis using stress formulation and experimental measurement using stress gauge show that in a loaded structural member, near to the changes in section, distribution of tensile stress occur in which the peak stress reaches much larger magnitudes than the average stress over the section. This increase in peak stress near holes, grooves, notches, sharp corners, cracks and other changes in section is called stress concentration. Fig. 11 shows the stress distribution.

4.3. DOF solution

This DOF Solution (Fig. 12) is given for having all active degrees of freedom in the model. Here, distribution is linear and varies slightly only. DOF solution is just the deformation solution in three axes. It can be seen that freedom in elements is more towards the

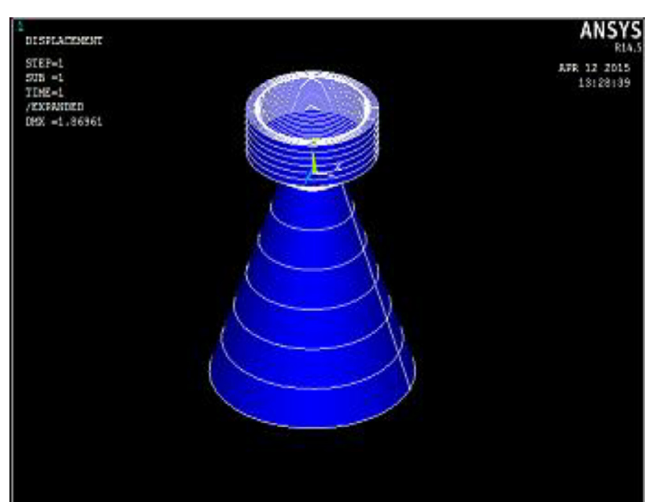

Fig. 10. Deformation plot.

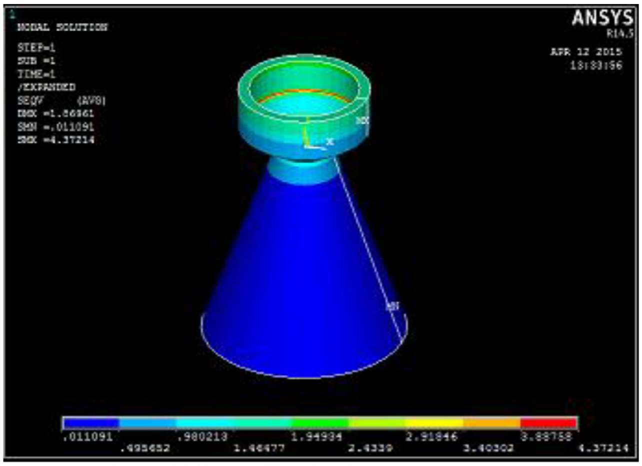

Fig. 11. Stress distribution.

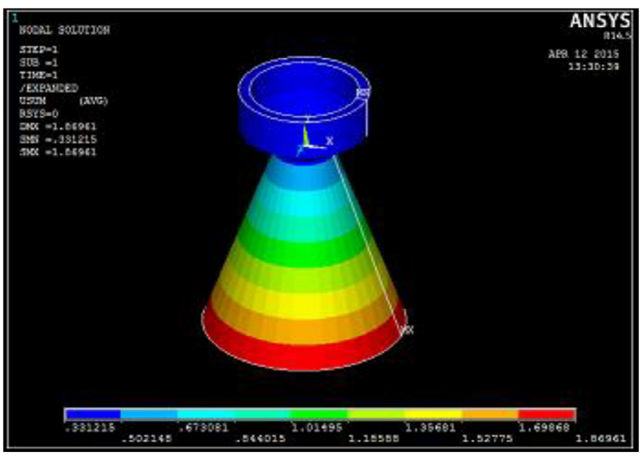

Fig. 12. DOF solution plot.

outer side. Also, values are same for DOF plot and deformation plot for a particular node.

4.4. Thermal gradient

Variation is mainly concentrated at corners. This is because temperature varies at corners due to stress concentration due to sharp corners as shown in Fig. 13.

4.5. Thermal flux

Thermal flux variation is concentrated at corners due to stress concentration as above cases. It is as shown in Fig. 14

4.6. Total Thermal & mechanical strain

Strain caused by thermal forces and mechanical forces combined are small but can cause issues due to combination with other factors. Hence, it becomes imperative for fillets at corners to avoid stress concentrations. Distribution of total thermal and mechanical strain is as shown in Fig. 15.

We can observe that the results obtained for case without fillet is on the high side resulting in poor design practice.

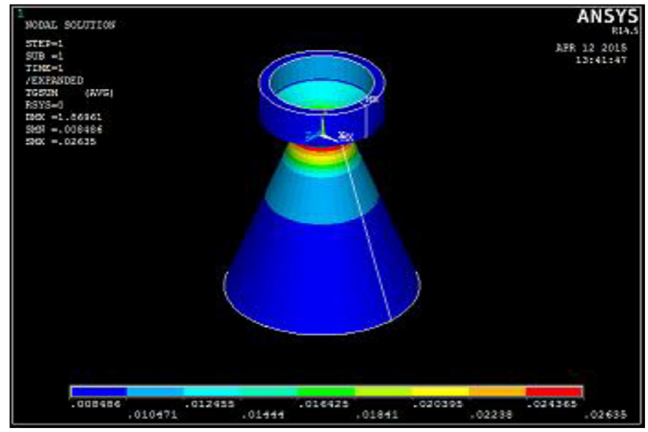

Fig. 13. Thermal Gradient distribution.

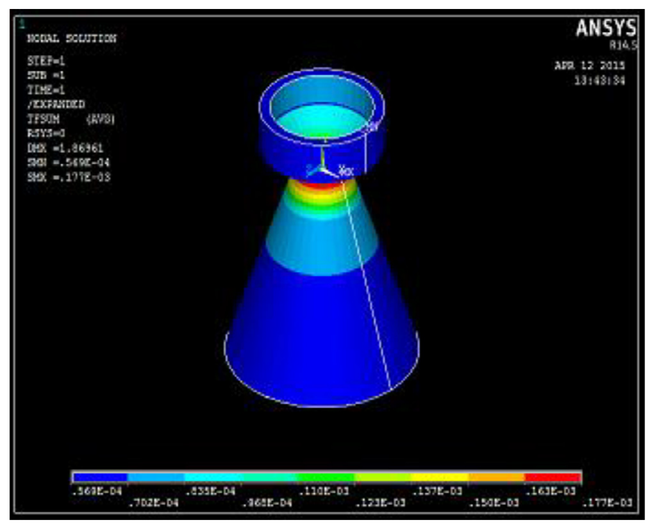

Fig. 14. Thermal Flux variation.

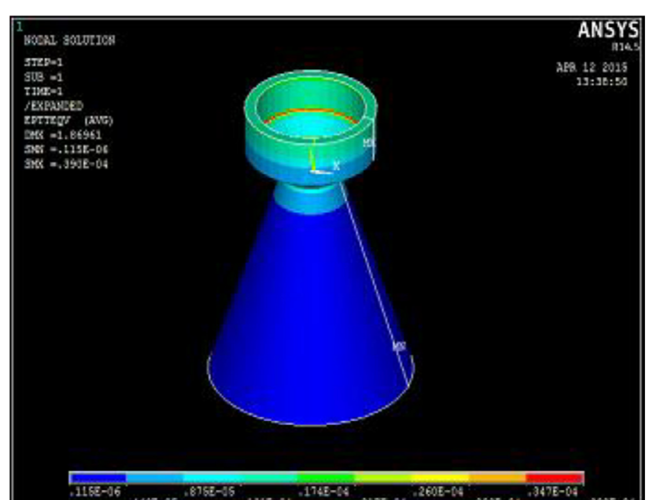

Fig. 15. Thermal and mechanical strain.

5. Results for case with fillets and arcs

5.1. Deformation

It is higher compared to non-filleted non-curved section although not much high in order to cause any issues. This can be explained by more uniform area available for deformation to spread. It is as shown in Fig. 16.

5.2. Stress

Tensile Stress concentration is decreased due to fillets and curved surface and is more or less distributed equally. It is as shown in Fig. 17.

5.3. DOF solution

DOF solution remains more or less same as deformation does not depend upon if there are fillets or not. It is shown below in Fig. 18.

5.4. Thermal gradient

Thermal gradient is very small, almost identical and is similar to other case as in Fig. 19.

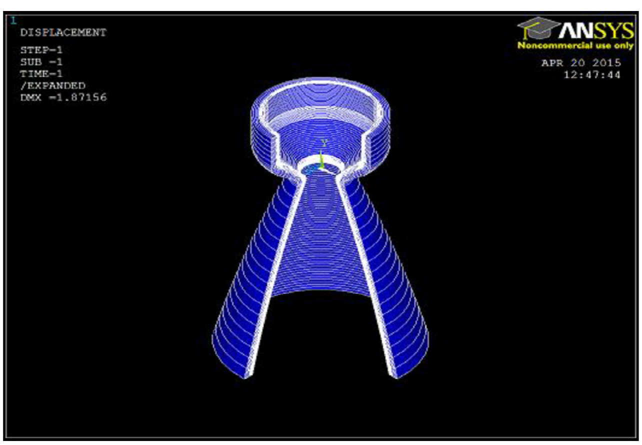

Fig. 16. Deformation plot.

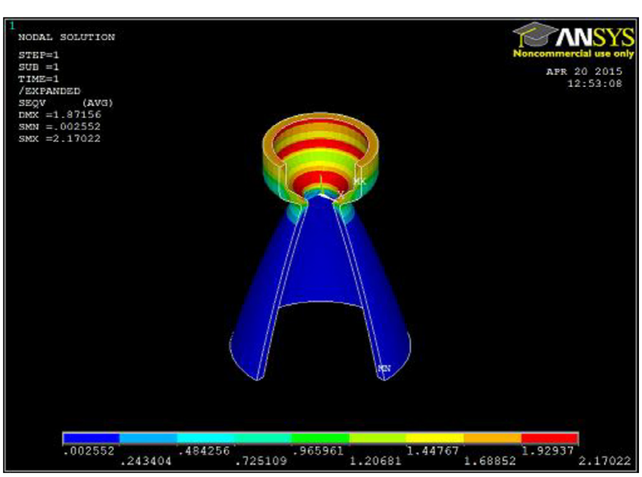

Fig. 17. Stress distribution.

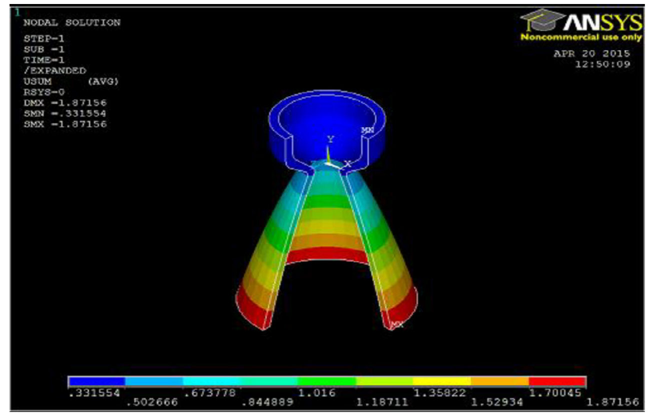

Fig. 18. DOF plot.

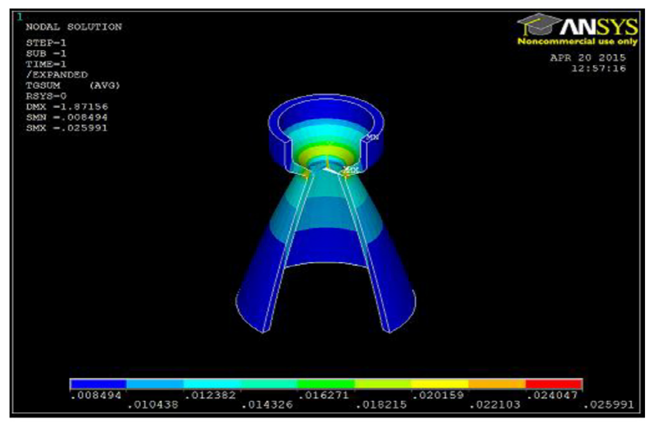

Fig. 19. Thermal gradient distribution.

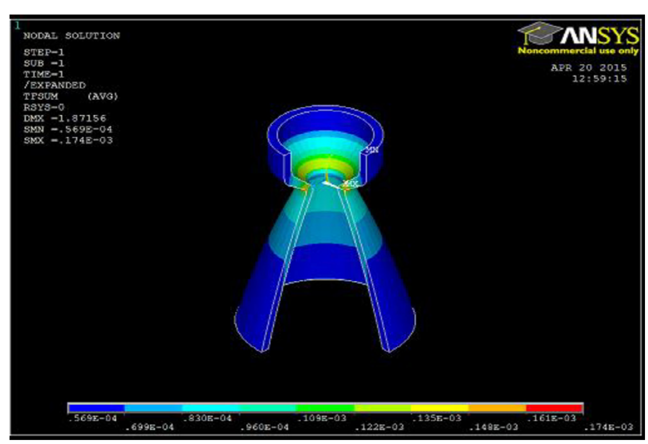

Fig. 20. Thermal Flux distribution.

5.5. Thermal flux

Thermal flux variation is very small and is identical to other case as shown in Fig. 20.

5.6. Total Thermal & mechanical strain

Total strain is very low having negligible variation as shown in Fig. 21.

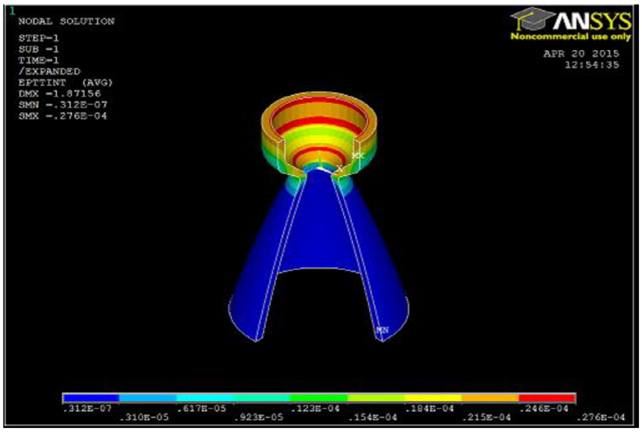

Fig. 21. Strain distribution.

We can see that results obtained by adding fillets are optimized for critical parameters hence implying improvement in design results in overall reduction of critical parameters of failure

6. Conclusions

The tensile stress is the only main variable. Therefore, it can be concluded that there is a significant decrease in stress value at the filleted configuration since stress concentration can be reduced by using fillets and curved sections. Not much deformation change is observed. Thermal gradient and thermal flux remains almost same implying that it doesn't depend on configuration but distribution pattern is more uniform in case with fillets and arcs. Overall strain is observed to be dissipated over a larger area and is mostly concentrated along fillets implying the necessity of the design. In Future, we can look into different parameters of fillet design to optimize parameters further in order to reduce failure.

CRediT authorship contribution statement

R. Harikrishnan: Conceptualization, Methodology, Data curation. **Lokavarapu Bhaskara Rao:** Conceptualization, Methodology, Visualization, Investigation, Validation, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] E. Madenci, I. Guven, The finite element method and applications in engineering using ANSYS, Springer 16 (2006) 15–35.
[2] A. Ogale, O. Marathe, S. Misal, N. Anekar, Design of nozzle and fin locking unit for MRECM rocket: a study, Int. J. Curr. Eng. Technol. 4 (2016) 347–351.
[3] Kumar B. Dinesh, Nayana B. Shishira, Shree D. Shravya, Design and structural analysis of solid rocket motor casing used in AE applications, J. Aeronaut. Aerospace Eng. 5 (2) (2016) 1–7.
[4] Stephen. Scampoli, Multiphysics Simulation using Directly Coupled Field Element Technology, ANSYS Advantage, 1(4), (2007) 30-31.
[5] R.R. Boyer, Overview of use of titanium in aerospace industry, Mater. Sci. Eng., A 213 (1996) 103–114.
[6] E.O. Ezugwu, J. Bonney, Y. Yamane, An overview of the machinability of aeroengine alloys, J. Mater. Process. Technol. 134 (2003) 233–253.
[7] Yves Honnorat, Issues and breakthroughs in the manufacture of turboengine titanium parts, Mater. Sci. Eng., A 213 (1996) 115–123.
[8] T.S. Lau, S.H. Lo, C.K. Lee, Generation of Quadrilateral Mesh over Analytical Curved Surfaces, Finite Elem. Anal. Des. 27 (1997) 251–272.
[9] R.D. Irwin, Static Thrust Augumentation of Rocket Motors', Technical Report WSRL-0332-T.R, Department of Defence, South Australia (1983).
[10] J. Cerantola David, Rocket Nozzle Design with Ejector Effect Potential', Thesis for the Degree of Master of Applied Science, Carleton University, Ottawa, Ontario, Canada (2007).
[11] Ostlund, Jan. Flow Process in Rocket Engine Nozzles', Technical Report ISSN 0348-467X, ISRN KTH/MEK/TR—02/09-SE, Royal Institute of Technology, Department of Mechanics, S-100 44 Stockholm, Sweden (2002).
[12] Taro. Shimizu, Masatoshi. Kodera, Nobuyuki. Tsuboi, Internal and External Flow of Rocket Nozzle, Journal of the Earth Simulator, 9, (2008) 19-26.
[13] Vipul. Sharma, Ravi. Shankar, Gaurav. Sharma, CFD Analysis of Rocket Nozzle, Technical Report for Bachelor of Technology, University of Petroleum & Energy Studies, Dehradun (2011).
[14] R. Howell John, K. Strite Mary, E. Renkel Harold, Analysis of Heat Transfer Effects in Rocket Nozzles Operating with Very High-Temperature Hydrogen, Nasa Technical Report, Lewis Research Center, Cleveland, Ohio (2011).
[15] Gerad. Hagemann, Hans. Immich, E. Dumnov Gennady, Advanced Rocket Nozzles, Journal of propulsion and power, 14(5), (1998) 620-634.
[16] Hu. Feng, Zhu. Hao, Cai, Guobiao, Uncertainty analysis and design optimization of solid rocket motors with finocyl grain, Structural Multidisciplinary Optimization , 2nd September (2020).
[17] M. Dito Saputra, Hendra. Gantina, Finite Element Modeling and Analysis of heat transfer in a 122-mm diameter solid rocket nozzle, AIP Conference Proceedings 2226, (2020) 040004
[18] Ansys APDL 14.5 User Manual.