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Design and Analysis of Rocket Nozzle to Determine Optimum Material and Fuel

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Abstract. Nozzle is considered as one of the most important parts of the rocket propulsion system. The thrust Produced by the Nozzle will determine the performance of the nozzle i.e., the amount of load that can be lifted by the nozzle against the gravity. Heavy rockets have nozzles that can lift higher loads. The thrust produced by the nozzle will depend on parameters such as velocity at exit of the nozzle, pressure at the exit of the nozzle and etc. The thrust produced by the nozzle will also depend on the type of the nozzle indirectly as various nozzles will have various properties. The exhaust gases produced after combustion when they pass through the nozzle the pressure energy of the flue gases will convert into the kinetic energy resulting the thrust required for the lift off. In this paper we designed the nozzles using Rocket propulsion analysis software and modelled using Solid works and analysed using ANSYS to determine the optimum nozzle design and the material is optimised by using the structural Analysis of the nozzles designed. The geometry parameters such as area expansion ratio, throat diameter and type of nozzle will influence the performance of the nozzle. The effect of the area expansion ratio on the performance will be discussed.

INTRODUCTION

The Project Mainly Deals with The Designing of the Rocket Nozzle. Rocket nozzle is one of The Important Aspect in the Rocket Propulsion System. It is the device that the pressure Energy of the system into kinetic energy which is used to produce the thrust required for the lift and travel of the rocket and space shuttle. Based on type of the flow at exit the nozzle Can be classified as sonic or supersonic [1-4]. The flow is subsonic at the inlet which is then accelerated at the throat to achieve the sonic velocity and further down the length it is accelerated to achieve supersonic velocities. The nozzle is optimised to achieve velocities without any shock waves and flow separation. So, nozzles are designed and then analysed using CFD Analysis to determine the best nozzle [5-9]. To get the best results the specific impulse should be maximum for a powerful rocket. The nozzle is designed, In Many aspects the geometry of the nozzle was taken and analysis was done and mainly few results include variation of performance parameters with the variation of geometry parameters and results prove that the geometric parameters influence the performance of nozzle[10-13]. In our case we designed the nozzle using Rocket Propulsion Software and along with the geometric parameter, the type of fuelis also considered. The geometric parameter considered here is area expansion ratio of nozzle. Structural Analysis was also performed to determine the stresses induced for various materials taken as nozzle material [14-17].

The Fig 1 shows depicts an actual nozzle that consists of subsonic, Transonic, and supersonic regions where the velocity of the fluid is measured with respect to the velocity of the sound. With the idea and emphasis on the rocket propulsion system, the nozzles and rockets became more efficient and rockets are designed based on the application. Each nozzle and corresponding geometry has their own applications [18-21].

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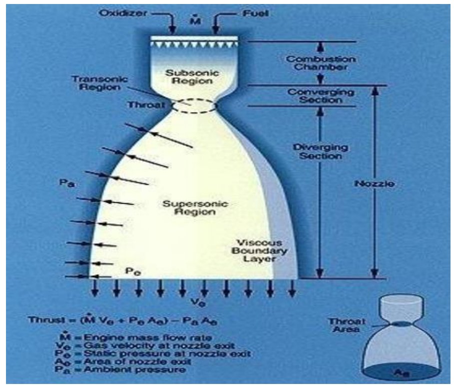

FIGURE 1. *Basic Rocket Nozzle*

Material Selection

The stress induced in the nozzle is very high which makes it very important to consider the type of nozzle material that is used. The melting temperature of the material should be appreciably high since the range of temperatures due to the flue gases will be very high. Here we did not consider the stresses induced due to the temperature only the stresses induced due to the pressure of the fluid flowing across the nozzle [22-24]. Considering the above criterion materials such as tungsten, tungsten carbides, titanium and niobium carbides serve the purpose. We are considering the materials tungsten Carbide and Niobium carbide for our analysis and determine the best out of the two materials as shown in Table 1. Above materials possess great structural characteristics namely young's modulus and bulk modulus which makes it great to serve the purpose [25-28].

Table 1. Material properties

	Niobium Carbide	**Tungsten Carbide**
Young's Modulus (MPa)	425	715
Bulk Modulus (MPa)	310	400
Density (kg/m3)	7.7	15.6
Melting Point (0C)	3520	2780
Thermal Conductivity(W/m-k)	14	84

MODELLING & ANALYSIS

Solid works software is used to model the nozzle structure that is later used for the analyses. The designing of the nozzle is generally performed using rocket propulsion analysis software which will gives the contour of the nozzle as result. The inputs are given to the software which will result in the nozzle contour. The inputs given to the software are chamber pressure of 5.85 MPa for each design, type of fuel and the geometric parameters whichis area expansion ratio is taken into consideration are taken by considering the optimum conditions and during designing nozzles with two fuel types namely

i. Hydrogen and Oxygen
ii. Methane and oxygen

Which are basic fuels used in the present day and the area expansion ratio of nozzles is taken as 20 and 10 respectively which resulted in four type of nozzle designs which are then modelled using Solid works.The nozzle contour designed by rocket propulsion analysis software is modelled using solid works [29-32]. The contour is imported to solid works and the nozzle is modelled using basic features, the thickness of the nozzle is taken as 50 mm as most of the current day nozzles have same thickness and a 3D model is designed for the structural analysis of the nozzle and a 2D model is designed for the flow analysis of the nozzle which helps in determining the velocity and finding the optimum design which results in more thrust [32-34].

Flow Analysis

Flow analysis is one of the most important types of analysis which determines various properties of fluid such as velocity, static pressure, dynamic pressure and Mach number and etc. The 2D model designed will be used for the flow analysis which is meshed initially and then the solution is obtained which will help us in

determining the change of performance due to change in the area expansion ratio Fig 2. The result contours consist of static pressure and velocity. The pressure is used in later stage for structural analysis of the nozzle andthe velocity may be used for determining the thrust produced by the nozzle.

Structural Analysis

Structural analysis is performed to determining how safe the object. The results of the structural analysis include von mises stress, shear stress, deformation and strain energy. These results will be used in determining how safe the structure is. The 3D model designed will be analysed by initially creating a 3D mesh on which the pressure load is applied due to fluid flowing across the nozzle as shown in Fig 3. And then it is solved to obtain the results for determining the optimum material. Figure 2 shows the 2D design of the nozzle used for the flow analysis and figure 3 shows the 3D nozzle used for the Structural analysis

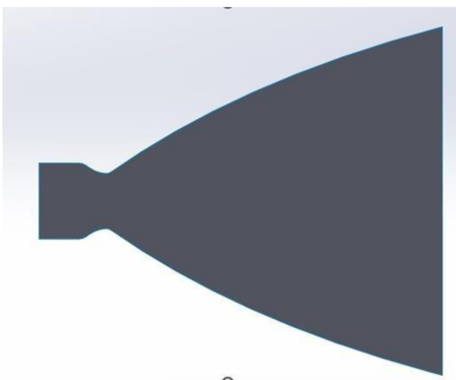

FIGURE 2. 2D Rocket Nozzle

FIGURE 3. 3D Rocket Nozzle

RESULTS AND DISCUSSION

The analyses are performed on the Nozzle and the following results are thus obtained and tabulated and compared and analysed. Then after analyses the best material and Fuel is selected. The results include various types of designs that we have considered for our analysis. The entire results are divided into four nozzle designs which are

i) Nozzle with H_2 and O_2 as propellant with area expansion ratio of 20
ii) Nozzle with H_2 and O_2 as propellant with area expansion ratio of 10
iii) Nozzle with CH_4 and O_2 as propellant with area expansion ratio of 20
iv) Nozzle with CH_4 and O_2 as propellant with area expansion ratio of 10

Also, two materials are considered for structural analysis which are Tungsten Carbide and Niobium Carbide of which the optimum material will be determined.

Flow analysis

The Results of flow analysis include Velocity profile of fluid and Static pressure for each case.

Fig 4 shows the magnitude of the velocity distribution of the design 1 nozzle and Fig 5 shows the static pressure contours that have been obtained from the flow analysis. The maximum velocity that has been obtained is about 3190 m/s whereas the maximum static pressure obtained is 5.91 MPa and the minimum static pressure obtained is 0.31 MPa. These pressures are used in further structural analysis of the nozzle, as this is the pressure applied on the nozzle which has larger impact.

Fig 6 shows the magnitude of the velocity distribution of the design 2 nozzle and Fig 7 shows the static pressure contours that have been obtained from the flow analysis. The maximum velocity that has been obtained is about 2580 m/s whereas the maximum static pressure obtained is 5.94 MPa and the minimum static pressure obtained is 0.291 MPa. These pressures are used in further structural analysis of the nozzle, as this is the pressure appliedon the nozzle which has larger impact.

Design.1: Nozzle with H_2 and O_2 as propellant with area expansion ratio of

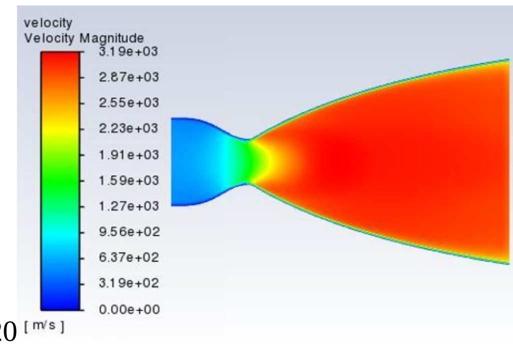

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FIGURE 4. Velocity Magnitude of Design 1

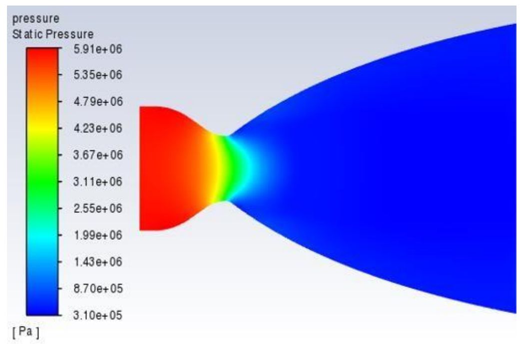


FIGURE 5. Nozzle Figure Static pressure of Design 1 Nozzle

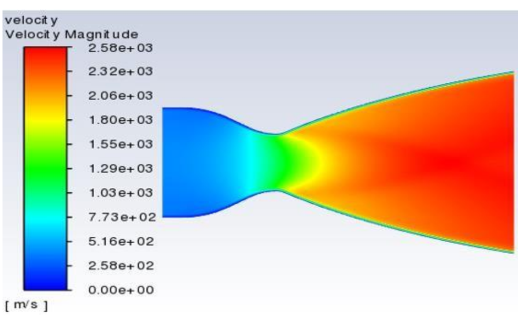


FIGURE 6. Velocity Magnitude of Design 2 Nozzle

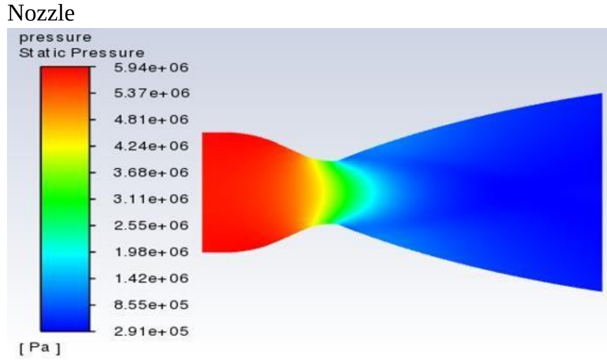


FIGURE 7. Static pressure of Design 2 Nozzle

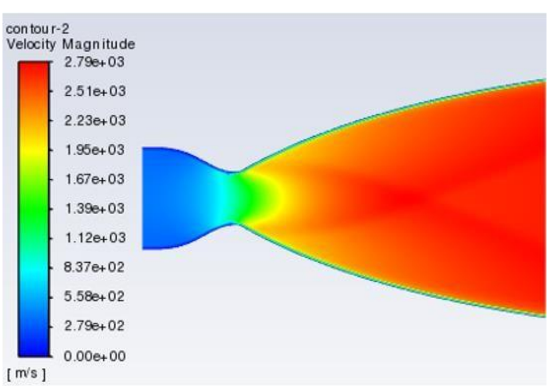


FIGURE 8. Velocity Magnitude of Design 3Nozzle

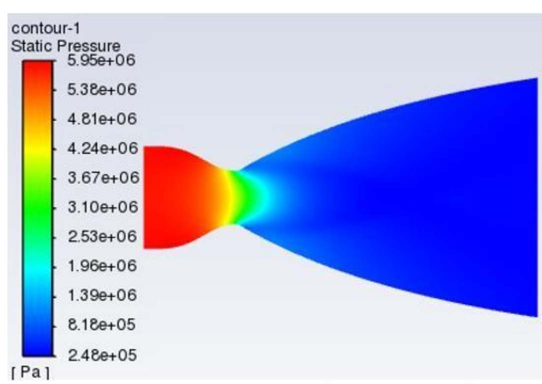
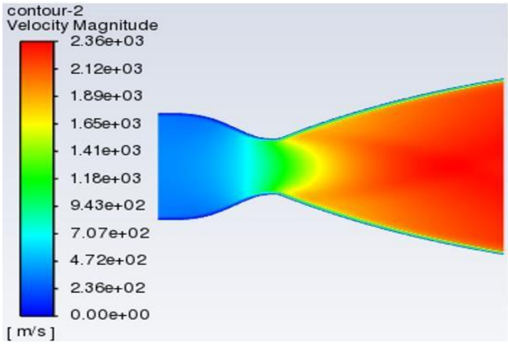


FIGURE 9. Static pressure of Design 3 Nozzle

Design4: Nozzle with CH_4 and O_2 as propellant with area expansion ratio of 10



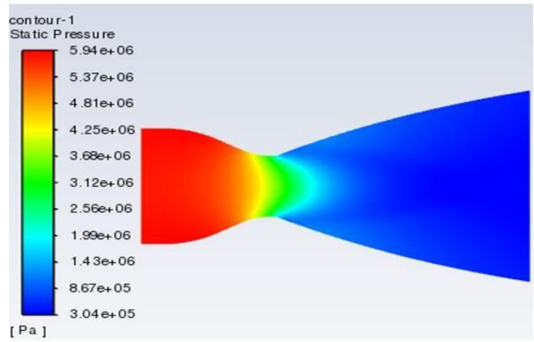


FIGURE 10. Velocity Magnitude of Design 4 Nozzle **FIGURE 11.** Static pressure of Design 4 Nozzle

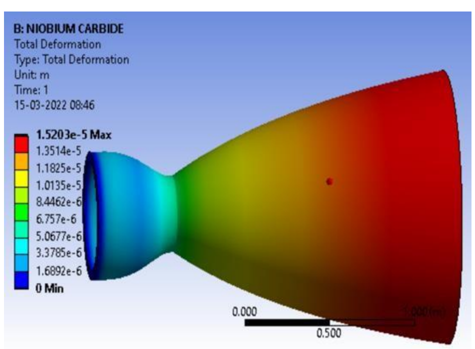
Fig 8 shows the magnitude of the velocity distribution of the design 3 nozzle and Fig 9 shows the static pressure contours that have been obtained from the flow analysis. The maximum velocity that has been obtained is about 2790 m/s whereas the maximum static pressure obtained is 5.95 MPa and the minimum static pressure obtained is 0.248 MPa. These pressures are used in further structural analysis of the nozzle, as this is the pressure applied on the nozzle which has larger impact. Fig 10 shows the magnitude of the velocity distribution of the design 4 nozzle and Fig 11 shows the static pressure contours that have been obtained from the flow analysis. The maximum velocity that has been obtained is about 2360 m/s whereas the maximum static pressure obtained is

5.94 MPa and the minimum static pressure obtained is 0.30 MPa. These pressures are used in further structural analysis of the nozzle, as this is the pressure applied on the nozzle which has larger impact.

Structural analysis

Structural analysis of the nozzle is performed to determine how safe the design. In this analysis the results include Total Deformation. The Results will determine the safety of the material by comparing stress induced with the ultimate strength of the material and deformations of the design is also considered as well.

Design.1: Nozzle with H_2 and O_2 as propellant with area expansion ratio of 20



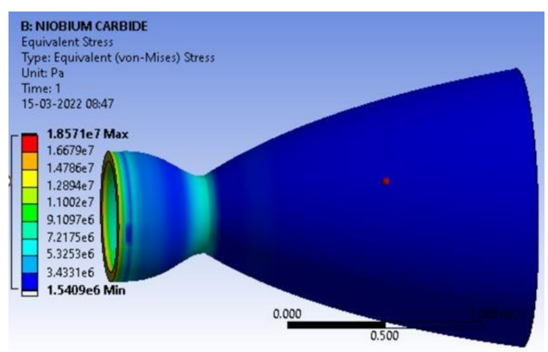
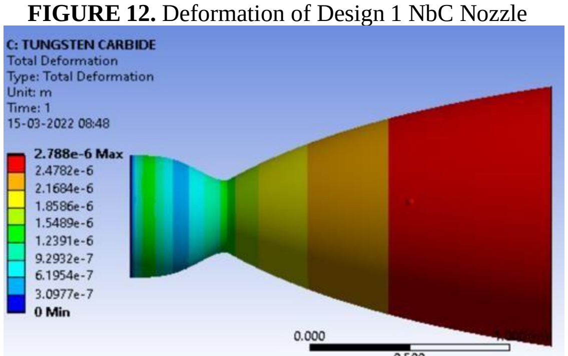


FIGURE 12. Deformation of Design 1 NbC Nozzle **FIGURE 13.** Von-Mises Stress of Design 1 NbC Nozzle



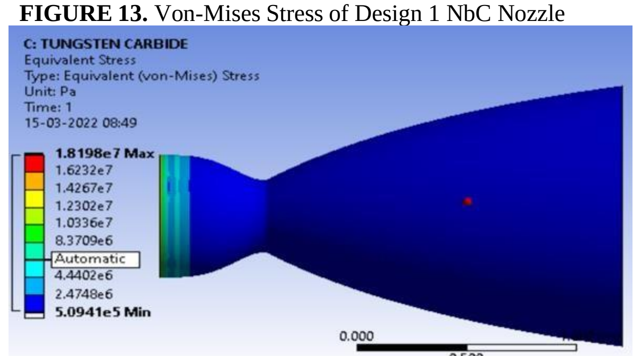


FIGURE 14. Deformation of Design 1 WC Nozzle **FIGURE 15.** Von-Mises Stress of Design 1 WC Nozzle

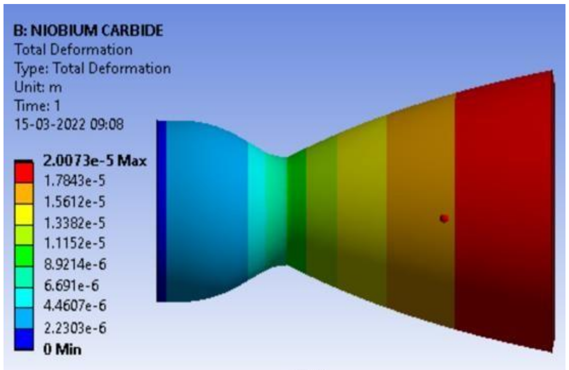


FIGURE 16. Deformation of Design 2 NbC Nozzle

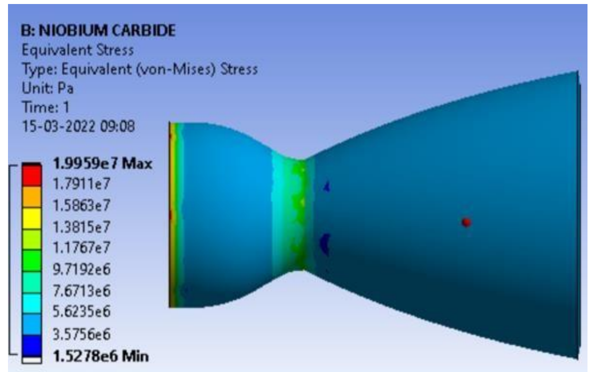


FIGURE 17. Von-Mises Stress of Design 2 NbC Nozzle

Fig 12 and Fig 13 show deformation and von-mises stress of design 1 respectively for niobium carbide. The max deformation is about 0.0152mm and max stress is about 18.5MPa. Fig 14 and Fig 15 shows the total deformation and von-mises stress respectively for tungsten carbide. The max deformation is about 0.00278mm and the max stress is about 18.19MPa.Design. 2: Nozzle with H_2 and O_2 as propellant with area expansion ratio of 10

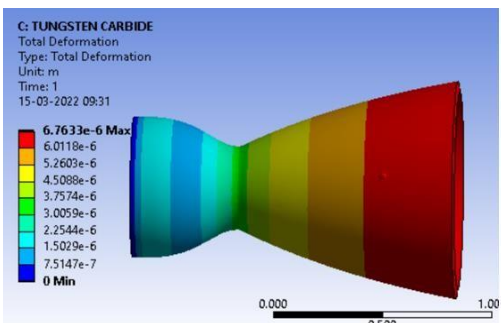


FIGURE 18. Deformation of Design 2 WC Nozzle

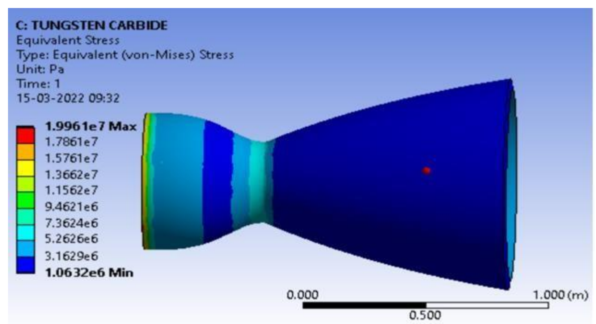


FIGURE 19. Von-Mises Stress of Design 2 WC Nozzle

Fig 16 and Fig 17 show deformation and von-mises stress of design 2 respectively for niobium carbide. The max deformation is about 0.02mm and max stress is about 19.95MPa. The Fig 18 and Fig 19 shows the total deformation and von-mises stress respectively for tungsten carbide. The max deformation is about 0.00676mmand the max stress is about 19.96MPa.

Design.3: Nozzle with H_2 and O_2 as propellant with area expansion ratio of 10

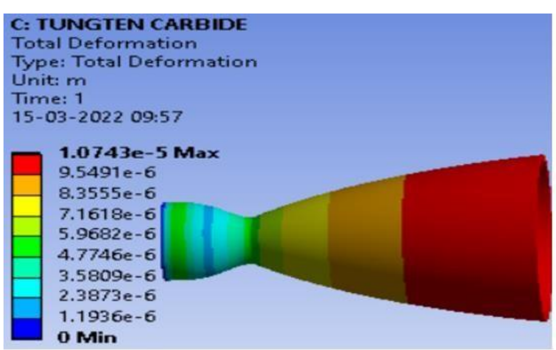


FIGURE 20. Deformation of Design 3 NbC Nozzle

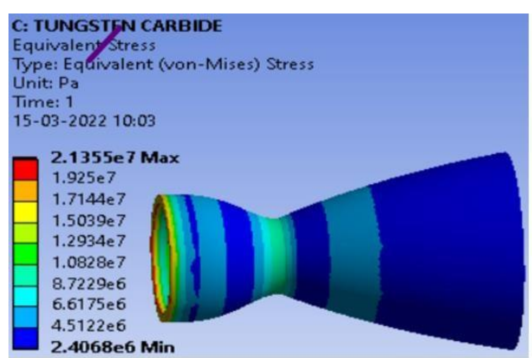


FIGURE 21. Von-Mises Stress of Design 3 NbC Nozzle

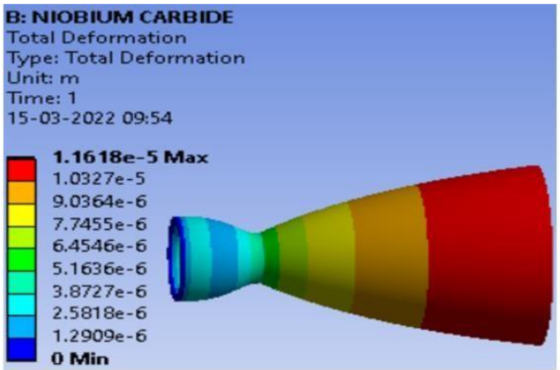


FIGURE 22. Deformation of Design 3 WC Nozzle

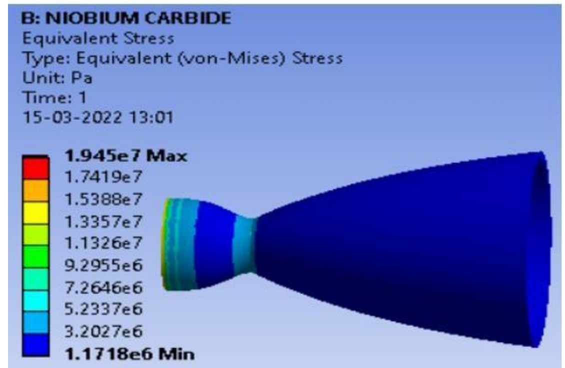


FIGURE 23. Von-Mises Stress of Design 3 WC Nozzle

Fig 20 and Fig 21 show deformation and von-mises stress of design 3 respectively for niobium carbide. The max deformation is about 0.016mm and max stress is about 19.45MPa. The Fig 22 and Fig 23 shows the total deformation and von-mises stress respectively for tungsten carbide. The max deformation is about 0.0106mm and the max stress is about 19.22MPa.

Design.4: Nozzle with CH_4 and O_2 as propellant with area expansion ratio of 10

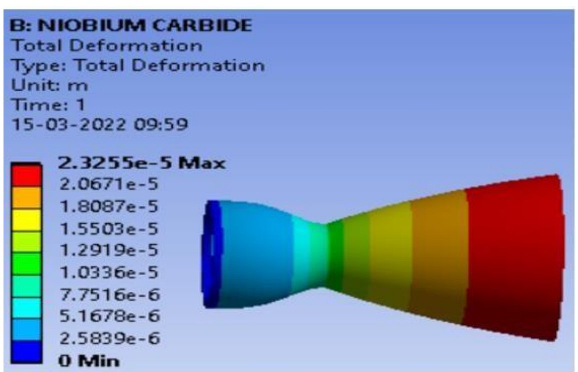


FIGURE 24. Deformation of Design 4 NbC Nozzle

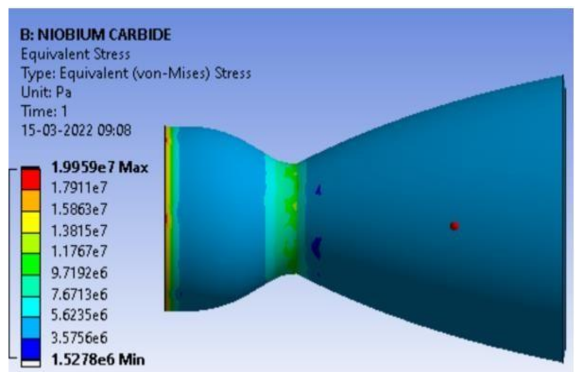


FIGURE 25. Von-Mises Stress of Design 4 NbC Nozzle

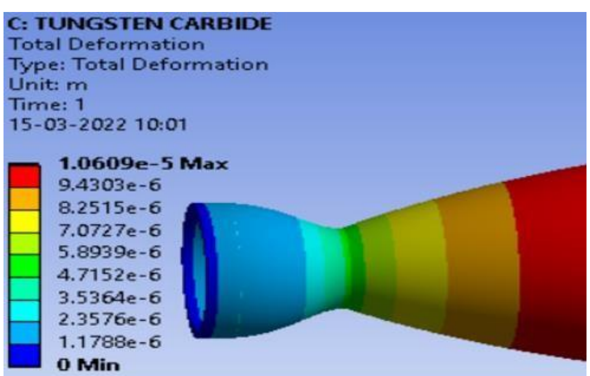


FIGURE 26. Deformation of Design 4 WC Nozzle

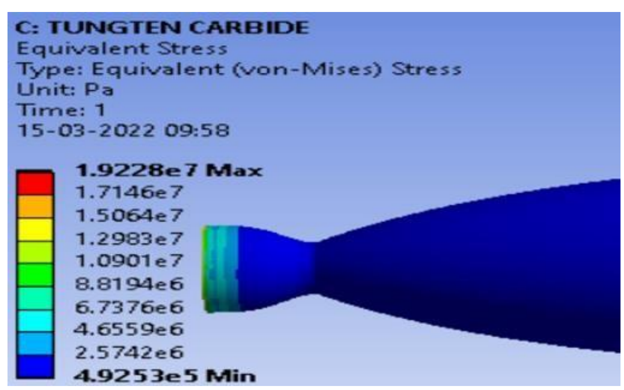


FIGURE 27. Von-Mises Stress of Design 4 WC Nozzle

Fig 24 and Fig 25 show deformation and von-mises stress of design 4 respectively for niobium carbide. The max deformation is about 0.0232mm and max stress is about 21.77MPa. The Fig 26 and Fig 27 shows the total deformation and von-mises stress respectively for tungsten carbide. The max deformation is about 0.0107mm and the max stress is about 21.35MPa.

Table 2. Flow Analysis Results

	Pressure (MPa)		Velocity(m/s)	
	Min	**Max**	**Min**	**Max**
Design 1	0.31	5.91	0	3190
Design 2	0.29	5.94	0	2580
Design 3	0.24	5.95	0	2790
Design 4	0.301	5.94	0	2360

Table 2 shows the flow analysis results for all designs that include the maximum and minimum values of velocity and static pressure. From above we can say that the pressure in each case of the nozzle is about same and velocity was maximum for design 1 which is 3190 m/s. Table 3 shows the structural analysis results for all designs which include the deformation and Von-Mises stress for each design using niobium carbide as the material and the results have been tabulated. From the above table it is found that design 1 has minimum stress while the deformations are comparable. So, design 1 is better.

Table 3. *Structural Analysis results for Niobium Carbide Material*

	Total Deformation (mm)		Von – Mises Stress (MPa)	
	Min	**Max**	**Min**	**Max**
Design 1	0	1.50*10-5	1.5	18.57
Design 2	0	2.0*10-5	1.52	19.95
Design 3	0	1.16*10-5	1.17	19.45
Design 4	0	2.32*10-5	2.82	21.77

Table 4. *Structural Analysis results for Tungsten Carbide material*

	Total Deformation (mm)		Von – Mises Stress (MPa)	
	Min	**Max**	**Min**	**Max**
Design 1	0	2.78*10-6	0.509	18.19
Design 2	0	6.76*10-6	1.06	19.96
Design 3	0	1.06*10-5	0.49	19.22
Design 4	0	1.07*10-5	2.4	21.35

Table 4 shows the structural analysis results for all designs which include the deformation and Von-Mises stress for each design using Tungsten carbide as the material and the results have been tabulated. From the above tableit is found that design 1 has minimum stress while the deformations are less as well. So, design 1 is better.

Table 5. *Thrust values obtained from Rocket Propulsion Analysis Software*

	Vacuum Thrust (KN)	Sea Level thrust (KN)
Design 1	758	720
Design 2	725	677
Design 3	741	697
Design 4	710	666

Table 5 shows the Thrust Values obtained from the RPA software and maximum thrust is obtained for Design 1 at both vacuum and sea level which concludes that design 1 is better. The results of four designs are given and the maximum values obtained are tabulated for each material and results include Velocity, Static pressure for flow analysis and Deformation, Von-Mises Stress for structural Analysis is, the Velocity is maximum for Design 1 which is more compared to that of other designs, Structural analysis results were found to be better for nozzle design 1, Tungsten carbide results were found to be better than Niobium carbide considering all the designs.

CONCLUSION

From above results both structural and Flow analysis conclude some results. From Flow results we conclude that the Nozzle with H_2 and O_2 as propellant and area expansion ratio of 20 has maximum velocity of 3190 m/s and the thrust produced is also higher which is 758 KN greatest of all nozzles concludes that this nozzle produces maximum thrust and can be used. So H_2 and O_2propellant found to be optimum when compared to CH_4 and O_2. Since it has low exit velocity when compared to other. From Structural analysis we can conclude that the Tungsten Carbide material has provided better results when compared to that of the Niobium Carbide, both deformation of 0.00676 mm and Von-Mises stress were less for Tungsten Carbide material of design 1 valued at 18.19 MPa, which was least for all designs and materials, and particularly in tungsten carbide material the nozzle with H_2 and O_2 as propellant and area expansion ratio of 20 has minimum stress and deformation, thus we can conclude that the Nozzle with H_2 and O_2 as propellent was found out to be optimum. Tungsten Carbide Material was found to be optimum. But to optimise the entire cost as well we can nozzle made of composite parts that are made of both niobium carbide and tungsten carbide as well and for outer sections, we can use titanium as well.

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