Design and Analysis of a Bell Type Rocket Nozzle

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Abstract - *Rocket nozzle is a propelling device used in rocket engines to expand and accelerate the combustion gases produced by burning propellants. Nozzle design is an iterative procedure in which aerodynamic, thermodynamic, structural and fabrication consideration are handled within the constraint to produce a preliminary nozzle design. The structural design objective of nozzle is to verify the sustainability of the nozzles' internal contour under such loads and to limit the stress generated in the structure to a suitable limit. The basic purpose of this study is to understand the effect various structural and thermal stresses and strains developed on the nozzle geometry. Nozzle geometry is one of the most important factors to understand the performance of a rocket. A poor nozzle geometry may result in poor performance of the rocket. In this paper we have designed a bell nozzle according to G.V.Rao method and have studied the effect of the forces on the contour of the nozzle. . The same atmosphere has been simulated in Ansys 2021 R2 Student version and the behavior was studied. The structural failure of rocket nozzle may occur if the stress exceeds the permissible limits. The aim of this study is to develop such a nozzle which is effective under extreme loads and has the capability to resist such loads*

Key Words: Ansys, Design, Rocket nozzle, Design methodology, Simulation, Bell nozzle, Rao's Nozzle.

1.INTRODUCTION

Nozzle is a device used to control the characteristics of a flowing fluid like the velocity of the fluid. A rocket nozzle is a device which expand high pressure and high temperature gases from subsonic level to supersonic level. Modern high energy solid propellant produces combustion gases of high temperature in order to enhance the specific impulse.

Types of rocket nozzle -:

- Bell type rocket nozzle.
- Conical rocket nozzle
- Aerospike nozzle
- Expansion-deflection(E-D) Nozzle.

In this paper we are going to study Bell type rocket nozzles. Bell nozzle is most commonly used in rockets because of its simple construction and advantages over conical nozzles.

A bell nozzle consists of two sections, Near the throat, the nozzle diverges at a relatively large angle but the degree of divergence tapers off further downstream. Near the nozzle exit, the divergence angle is very small. In this way, the bell is a compromise between the two extremes of the conical nozzle since it minimizes weight while maximizing performance. The most important design issue is to contour the nozzle to avoid oblique shocks and maximize performance.

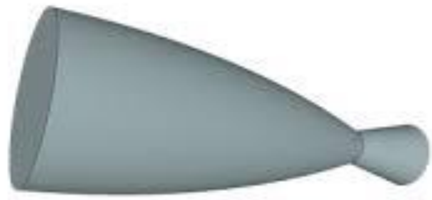

Fig -1: Bell nozzle

Parts of a bell type rocket nozzle-:

- Convergent section
- Throat
- Divergent section
- Exit

2. DESIGN METHODOLOGY

There are many steps in the design of a rocket nozzle It is a complicated and long process which involves many steps. A detailed flow chart has been provided in the next page which describes all the process involved in the design of Bell nozzle.

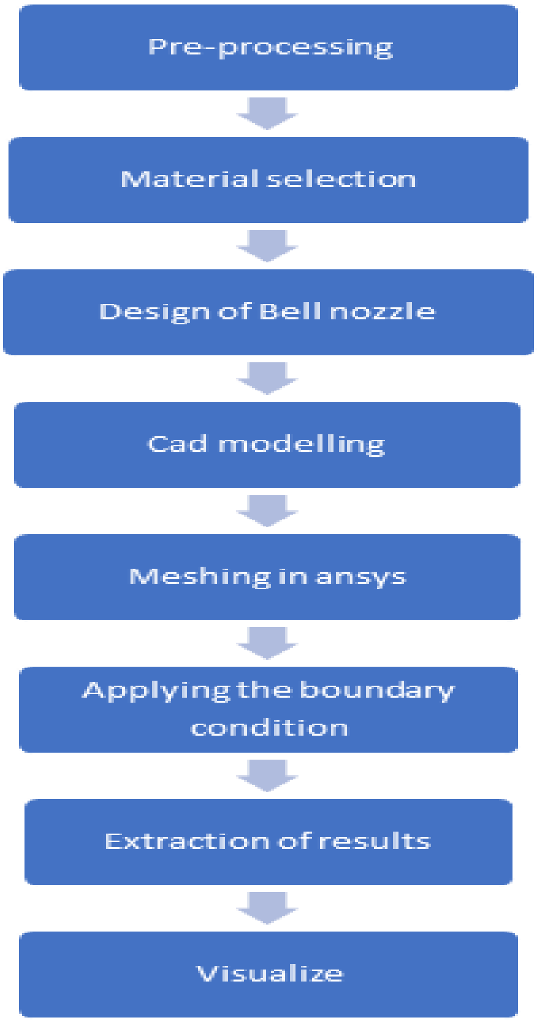

Fig -2: Flow chart describing the design methodology of bell nozzle.

2.1 PRE PROCESSING

In general terms it is the preliminary processing of the work . It involves determination of what methods shall be used to design what are the methods to be used for fabrication and determination of boundary condition.

We have determined to use G.V.Rao method and details of the boundary condition are mentioned in the upcoming pages of this paper.

2.2 MATERIAL SELECTION

A rocket nozzle is generally made up of composites which comprises Aluminum 7075, Silica phenolic, Carbon phenolic and Graphite.

The properties of these materials have been described in the below table.

Table-1: Properties of materials used in nozzle

Material	Youngs modulus (MPa)	Poisson's ratio	Ultimate tensile strength (MPa)	Density (Kg/m^3)
Graphite	1180	0.3	10.5	1900
Carbon phenolic	900	0.25	10	1350
Silica phenolic	1700	0.28	9	1350
Aluminum 7075	7378	0.33	42.9	2700

2.3 DESIGN

We have used G.V.Rao method for designing of the nozzle.The following assumption were made for the design of the nozzle-:

- The combustion gases are homogenous i.e.,
  P= ρRT, Where,
  P is the Pressure
  ρ is the density
  R is the universal gas constant
  T is the temperature.
- The particular heats of the gases don't vary much with temperature and pressure.
- The flow is meant to be one-dimensional and steady.

2.3.1 CONTOUR DESIGN OF THE NOZZLE-:

There are two types of nozzle contours conical and contoured. In this paper we will design a contoured type nozzle.

A bell nozzle is constructed using three curves.

a) An initial circle coming from inlet to throat.
b) A smaller circle exiting the throat.
c) A parabola that extends till the exit of the nozzle.

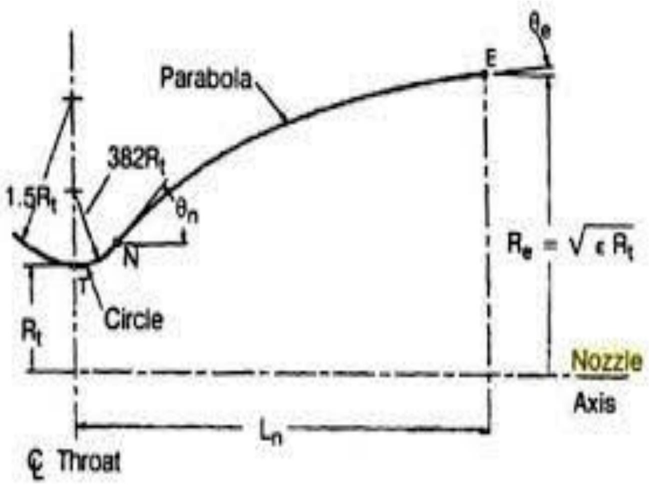

Fig-3: Rao's Bell nozzle contour.

Here Length of nozzle =Ln= $\frac{K(\sqrt{\epsilon}-1)Rt}{\tan(\theta e)}$

where K is a value chosen based on the percent of the length of a conical nozzle with a 15° half angle. The equation of the parabola takes the form

$x=ay^2+by+c$

The coefficients of the parabola can be determined from the condition that the beginning of parabola meets the circle at of the throat.
We also use the length of the nozzle as a condition to determine the value of the coefficient of the parabola.

2.4 CAD MODELLING

Computer-aided design is the use of computers to aid in the creation, modification, analysis, or optimization of a design .CAD modelling is a process which allows designer to visualize the product even before its production. That CAD model can then be used to test, refine and manipulate virtual products in a virtual environment. We have used Solidworks 2018 for CAD modelling of the bell nozzle.

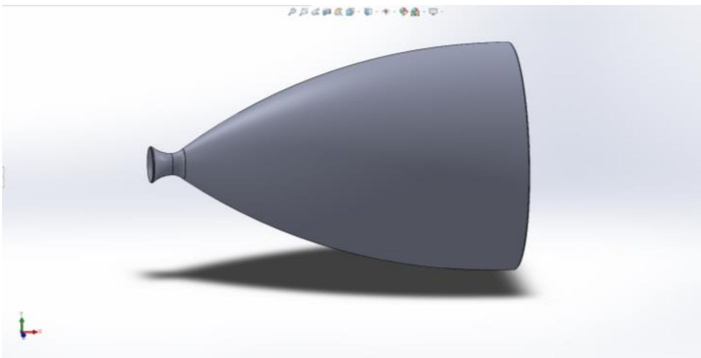

Fig-4: CAD model of bell nozzle used for study in this paper

2.5 MESHING IN ANSYS

There are basically three methods for solving an engineering problem

- Analytical method- In this method various functions and equations are used to find output variables & derive closed form solutions.
- Numerical method- It is used CAE engineers and analysts. It builds mathematical model to replicate complex problems, it also makes many assumptions to simulate the problem. It is of 4 types:
  - a) Finite element method
  - b) Boundary element method
  - c) Finite volume method
  - d) Finite difference method
- Experimental method- It involves testing on the prototype. It is the most reliable method and used in industry before final approval.

In this paper we have used Finite element method of solving the problem. The whole model is divided into finite number of parts and the mathematical model is built and the simulation is done.

2.6 BOUNDARY CONDITION

These are the constraints required for solving a boundary valued problem. Boundary condition used in this problem are-

- The end attached to the combustion chamber is assumed to fixed support.
- The other end is assumed as free end as it has no rigid support attached to it.
- The chamber pressure was estimated to be 5.3 Mpa
- The chamber temperature was estimated to be 3000.12k.

2.7 EXTRACTION OF RESULTS

After solving the model in ANSYS multiple system model we have found the following results. The results have been tabulated below.

Table -2: Tabulation of the result

S.no	Factor	Numerical Value	
		Avg	Max
1	Elastic stress (Mpa)	548.65	13081.00

2	Elastic strain	0.0028	0.0905
3	Total deformation (mm)	95.309	146.98
4	Thermal strain	0.0031	0.0032

2.8 VISUALIZATION OF RESULTS

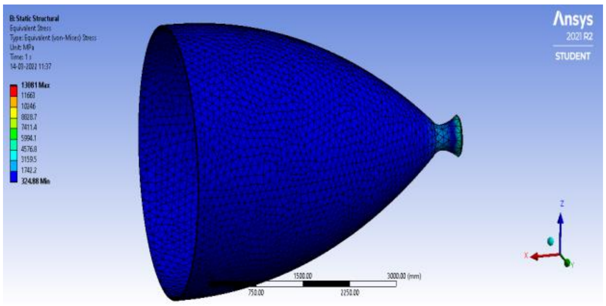

Fig-5: Equivalent elastic stress on the bell nozzle.

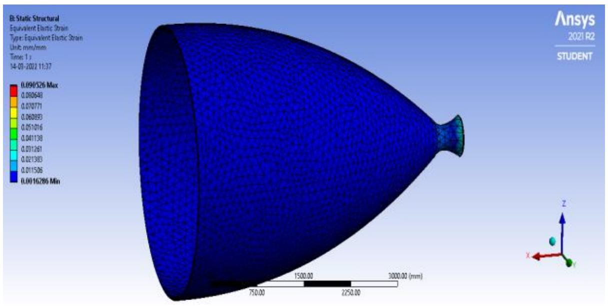

Fig-6: Equivalent elastic strain on the bell nozzle.

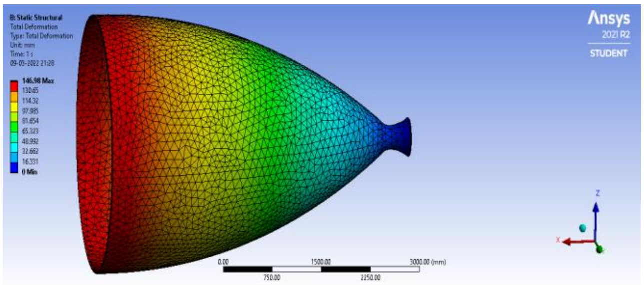

Fig-7: Total deformation of the bell nozzle.

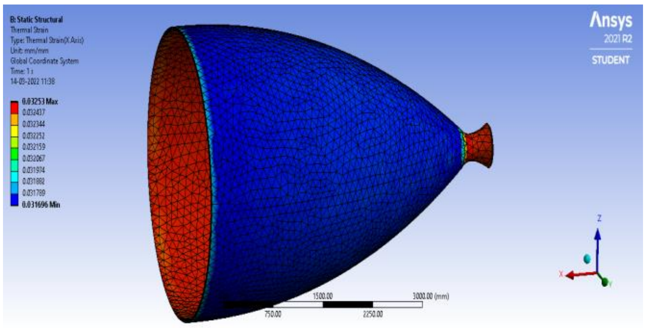

Fig-8: Thermal strain on the bell nozzle.

3. CONCLUSIONS

This paper was a detailed study on the design of a bell type nozzle using G.V.Rao method. To verify whether our design could sustain the stresses without suffering any major deformation and the stresses produced doesn't produce any significant change in the contour of the nozzle.

We have found out from this work that the stresses produced are much below the limit.

We have performed the analysis to get a stable structure.

4. REFERENCES

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