Analysis of Rocket Nozzle with 1 and 4 Inlets

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Abstract - *A Rocket Nozzle is a mechanical device of varying cross sections modelled to control the rate of flow, speed, direction and pressure of the exhaust gases coming from the combustion chamber. A De Laval Nozzle is a convergent-divergent nozzle, in which the temperature from the combustion chamber increases rapidly into convergent part of the nozzle, after which the temperature will decrease at the exit part of the nozzle. This project deals with CFD analysis of a De Laval nozzle based on number of inlets (one and four) from combustion chamber. The CFD analysis is done to calculate the exit temperature, exit pressure and exit velocity of the De Laval nozzle. These parameters are calculated by varying the Mach number. This analysis will result in a comparative study of the performance of a single inlet nozzle and four inlets nozzle at different Mach Numbers (subsonic, sonic and supersonic). The numerical analysis is carried out using a Computational Fluid Dynamics (CFD) Software, ANSYS Fluent.*

***Key Words*: Nozzle, Temperature, Pressure, Velocity, Mach Number.**

1.INTRODUCTION

The nozzle is a device that converts enthalpy into kinetic energy with no moving parts. Nozzle is a tube with variable cross-sectional area. It is used to give direction to the gases coming out of the combustion chamber. Nozzles are generally used to control the rate of flow, speed, direction, mass, shape, and the pressure of the exhaust stream that emerges from them.

Rockets having high performance engines usually incorporate a convergent-divergent nozzle. An exhaust nozzle is used to increase the velocity of the exhaust gas before discharge into atmosphere and to collect and straighten the gas flow. In this paper, we consider that:

- All the species of the working fluid are gaseous.
- There is no heat transfer across the rocket nozzle walls. Therefore, the flow is adiabatic.
- There is no appreciable friction and all boundary layer effects are neglected.
- There are no shock waves or discontinuity in the nozzle flow.
- The propellant flow is steady and constant. The expansion of working fluid is uniform and steady, without vibration.
- All exhaust gases leaving the rocket have an axially directed velocity.
- The gas velocity, pressure, temperature and density are all uniform across any section normal to the nozzle axis.
- Chemical equilibrium is established within the rocket chamber and the gas composition does not change in the nozzle.

These assumptions allow us to imply that the nozzle flow is thermodynamically reversible.

The number of inlets to a nozzle decides the inlet pressure and mass flow through it. The higher the number inlets, higher the inlet pressure and higher the mass flow. It then causes substantial change in the nozzle exit velocity. This depicts the significance of the effect of the number of inlets to the rocket nozzle from combustion chamber.

1.1 De Laval Nozzle

Gustaf de Laval, a Swedish inventor, invented the De Laval Nozzle. The converging-diverging nozzle, is normally used to supply super-sonic jet velocity at the exit of the nozzle. In the convergent section of the nozzle, the pressure of the exhaust gases will increase and as the hot gases expand through the diverging section attaining high velocities. In the nozzle, the combustion chamber pressure is decreases as the flow propagates towards the exit as compared to the ambient pressure i.e., pressure outside the nozzle. This results in maximum expansion known as optimum expansion.

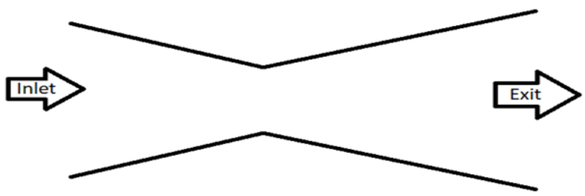

Fig -1: De Laval Nozzle

2. LITERATURE SURVEY

K. M. Pandey [1] has conducted a CFD Analysis on four inlet rocket nozzles with a Mach Number of 2.1. The paper showed light on the CFD analysis of the pressure and temperature of the nozzle with four inlets. The Mach Number was kept constant and flow analysis was performed.

Pandey et.al [2] performed a CFD Analysis of a Rocket Nozzle with Two Inlets at Mach 2.1. The outcomes, pressure and temperature, for a rocket nozzle with two inlets, were analysed with the help of ANSYS FLUENT.

Biju Kuttan et.al [3] performed a numerical analysis to find the required divergent angle for the nozzle which will give the maximum outlet velocity and satisfy the thrust requirements. The boundary conditions were saved constant and the divergent angles were varied. It was then realized, how the variation in divergent angle affects the flow through the nozzle.

Surya Narayana et.al [4] analysed a convergent-divergent rocket nozzle which was performed by varying the number of divisions in the mesh. The various contours of the nozzle like Cell equi-angle skew, Cell Reynolds number, Pressure, Velocity, Mach Number, and above are calculated at each type of mesh using CFD analysis software ANSYS Fluent.

Madhu BP et.al [5] performed a study using super-sonic flow is conducted on a Rocket nozzle. It was performed using the numerical method. The parameters, Mach number, static pressure and shocks, were observed for conical and contour nozzles using the axisymmetric model in ANSYS FLUENT software. The results of the convergent-divergent nozzle and contour nozzle were compared by keeping the outlet, inlet, lengths and throat diameter of convergent and divergent nozzles as constant.

2.1 Research Gap

The expansion analysis has been done only for individual rocket nozzles at a particular Mach Number. So, there is no sufficient work done on the supersonic, sonic, and subsonic speeds at the rocket nozzle.

None of the studies has compared the supersonic, sonic, and subsonic speeds of single and four inlet rocket nozzles.

2.2 Objectives

The objective of the present work is:

- To perform CFD Analysis of a De Laval Nozzle with one and four inlets using ANSYS FLUENT.
- To perform a comparative study of the performance of De Laval Nozzle for a different number of inlets based on exit temperature, exit pressure and velocity, by varying the Mach Number (subsonic, sonic and supersonic).

3. METHODOLOGY

A comparative analysis is carried out for a single inlet and four inlet rocket nozzles at subsonic, sonic, and supersonic speeds by varying the Mach Numbers. The project methodology is depicted in the flow chart.

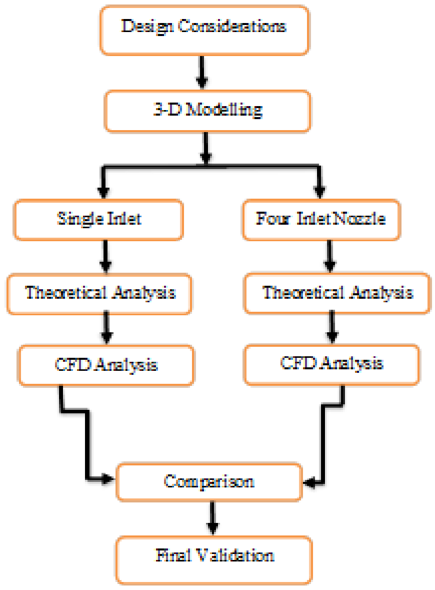

Chart -1: Methodology Flowchart

4. MODELLING OF DE LAVAL NOZZLE

The modelling of the De Laval rocket nozzle is done based on the previous studies [4]. This design is used for both, single and four inlets, nozzles.

Table -1: Dimensions of Nozzle

Dimensions of the Nozzle	
Inlet Diameter	25mm
Exit Diameter	35mm
Throat	10mm
Length of the nozzle	75mm

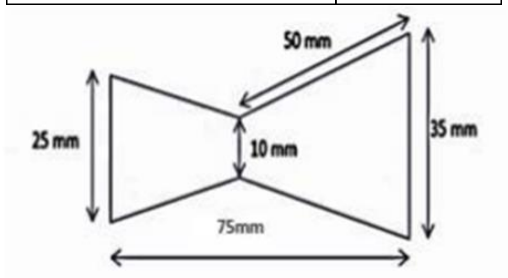

Fig -2: Side view of Nozzle

5. THEORETICAL CALCULATIONS

The calculations are performed using the Rocket Thrust equations. The working fluid is taken as air.

Ideal combustion chamber pressure is taken between 1-20 MPa. Ideal combustion chamber temperature is taken as 3200 ^{0}C.

We consider,

Combustion Chamber Pressure (P_t) = 20 MPa

Combustion Chamber Temperature (T_t) = 3500K

Specific heat ratio (γ) = 1.2

Gas Constant (R) = 0.287 KJ/kg-K

To calculate the exit temperature, pressure, velocity and thrust,

Exit Temperature Ratio

$$\frac{T_e}{T_t} = \left(1 + \left(\frac{\gamma - 1}{2}\right) M^2\right)^{-1} \quad \text{.........(1.1)}$$

Exit Pressure Ratio

$$\frac{P_e}{P_t} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{-\frac{\gamma}{\gamma - 1}} \quad \text{............(1.2)}$$

Exit Velocity $V_e = M(\sqrt{\gamma R T_e})$ ....(1.3)

Where,

Mach Number - M, Exit Temperature - T_e, Exit Pressure - P_e, Area of cross section at the exit – A_e , Free Stream Pressure – P_o

5.1 For Single Inlet Nozzle:

At Mach 2.5:

Using equation (1.2) to find exit pressure,

$$\frac{P_e}{P_t} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{-\frac{\gamma}{\gamma - 1}}$$

$$P_e = 20\left(\left(1 + \left(\frac{1.2 - 1}{2}\right)(2.5)^2\right)\right)^{-\frac{1.2}{0.2}}$$

P_e=1.0862 MPa

Using equation (1.1) to find exit temperature,

$$\frac{T_e}{T_t} = \left(1 + \left(\frac{\gamma - 1}{2}\right) M^2\right)^{-1}$$

$$T_e = 3200\left(1 + \left(\frac{1.2 - 1}{2}\right)(2.5)^2\right)^{-1}$$

T_e=1969.23 ^{0}C

Using equation (1.3) to find the exit velocity,

$$V_e = M\sqrt{\gamma R T_e}$$

$$V_e = 2.5\sqrt{1.2 * 0.287 * 1969.23}$$

V_e= 65.1058 m/s

Similarly, for Mach 1 and Mach 0.6, using the same formulae:

Mach 1: P_e= 11.28MPa, T_e= 2908.8^{0}C, V_e=33.103 m/s

Mach 0.5: P_e=17.246 MPa, T_e=3123.2 ^{0}C, V_e=17.1 m/s

5.2 For Four Inlet Nozzle:

Taking Ideal conditions, we consider,

Combustion Chambers Pressure (P_t) = 80 MPa

Combustion Chamber Temperature (T_t) = 3500K

Specific heat ratio (γ) = 1.2

Gas Constant (R) = 0.287 KJ/kg-K

Using the same formulae for four inlet nozzle:

Mach 2.5: P_e=4.3448 MPa, T_e=1969.23 ^{0}C, V_e= 65.1058 m/s

Mach 1: P_e= 45.158 MPa, T_e= 2908.8^{0}C, V_e=33.103 m/s

Mach 0.5: P_e= 68.984 MPa, T_e=3123.2 ^{0}C, V_e=17.1 m/s

6. ANALYSIS OF THE NOZZLES

The analysis is carried out mainly using ANSYS Software. It allows transferring of the model from CAD to ANSYS.

6.1 Meshing and Boundary Conditions

The meshing of the nozzles is done using the ANSYS Software. The Automatic Mesh function is used for Meshing for the Single and Four Inlet Nozzle. The mesh is split over three sections of the nozzle, inlet, wall and, outlet.

The parameters setup is discussed in the table below.

Table -2: Boundary Conditions for Analysis

Boundary Conditions	
General	Type: Density-based Velocity: Absolute Time: Steady

	2D space: Planar
Models	Energy: On Viscous: Inviscid
Materials	Fluid: Air Density: Ideal Gas Viscosity: Sutherland
Boundary Conditions	Inlet: Pressure Inlet Outlet: Pressure Outlet Gauge Pressure: 0 Pa Type: Symmetry
Initialization	Standard Initialization Compute from Inlet

6.2 Solutions for Single Inlet Nozzle

Pressure Variation

The Combustion chamber pressure is taken to be between 1-20 MPa, with a gas constant of 0.287 KJ/Kg-K. The output of the analysis is shown in the figures below.

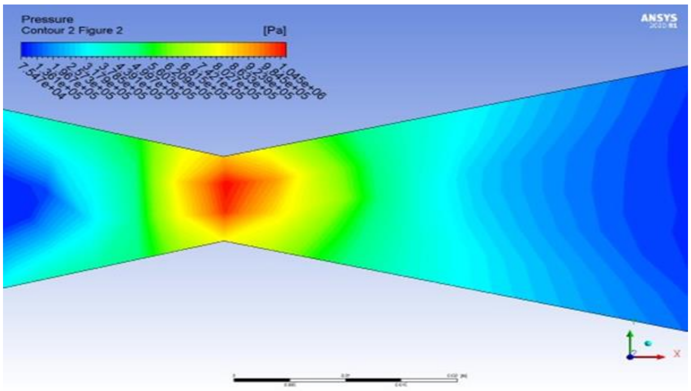

Fig -3: Pressure Variation at Mach 0.5

The minimum pressure of 7.547 e^04 Pa and the maximum pressure of 1.045 e^06 Pa is experienced in the Single Inlet Rocket Nozzle at Mach 0.5.

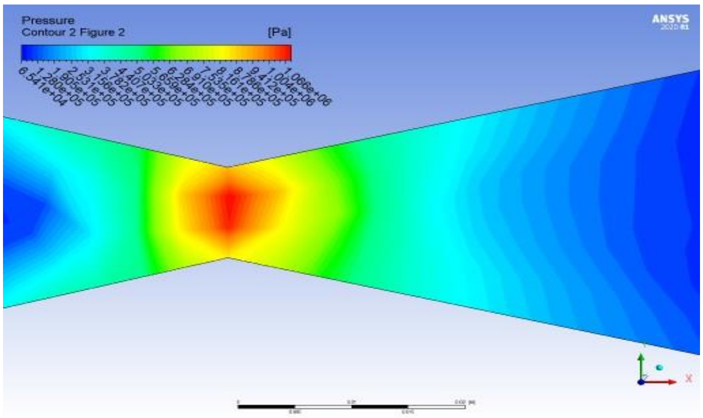

Fig -4: Pressure Variation at Mach 1

The minimum pressure of 6.541 e^04 Pa and the maximum pressure of 1.066 e^06 Pa is experienced in the Single Inlet Rocket Nozzle at Mach 1.

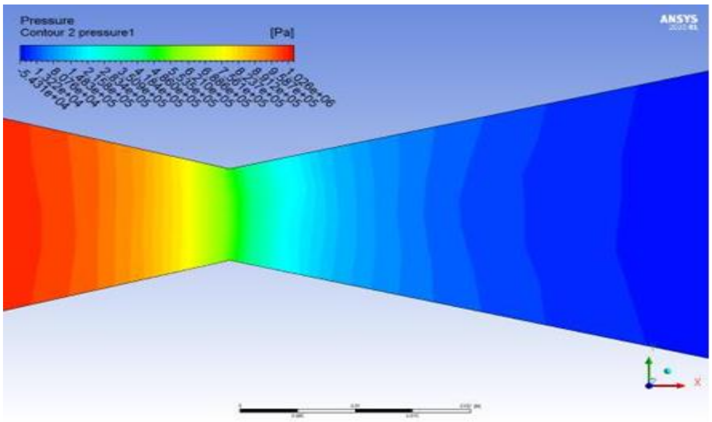

Fig -5: Pressure Variation at Mach 2.5

The minimum pressure -5.431 e^04 Pa and the maximum pressure 1.026 e^06 Pa is experienced in the Single Inlet Rocket Nozzle at Mach 2.5.

Temperature Variation

The Ideal temperature for a combustion chamber is taken as 3200K and the specific heat ratio as 1.2. The fluid considered is Air. The output of the analysis is shown below.

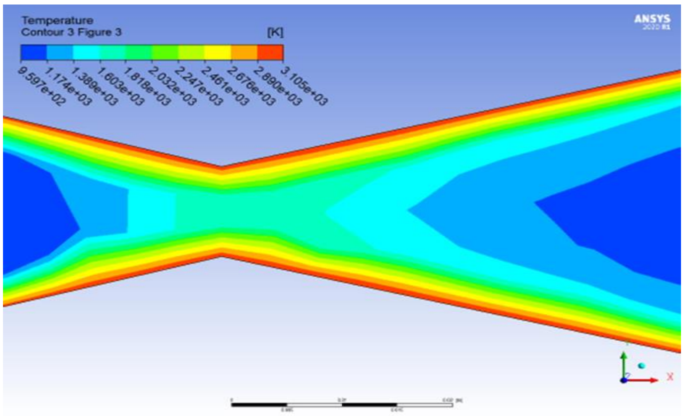

Fig -6: Temperature Variation at Mach 0.5

The minimum temperature of 9.597 e^02 K and the maximum temperature of 3.105e^03 K is experienced in the Single Inlet Rocket Nozzle at Mach 0.5.

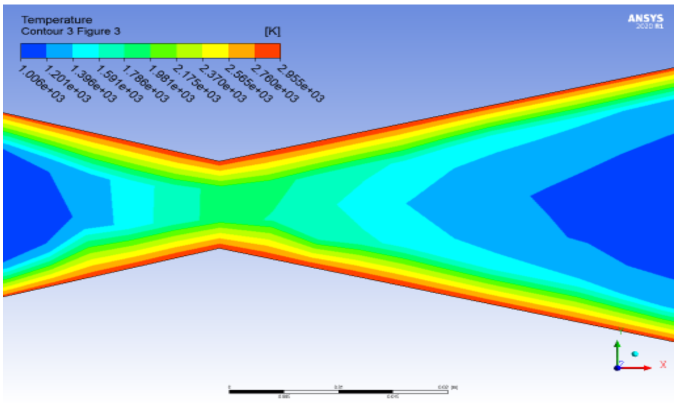

Fig -7: Temperature Variation at Mach 1

The minimum temperature of 1.006 e^03 K and the maximum temperature 2.955 e^03 K is experienced in the Single Inlet Rocket Nozzle at Mach 1.

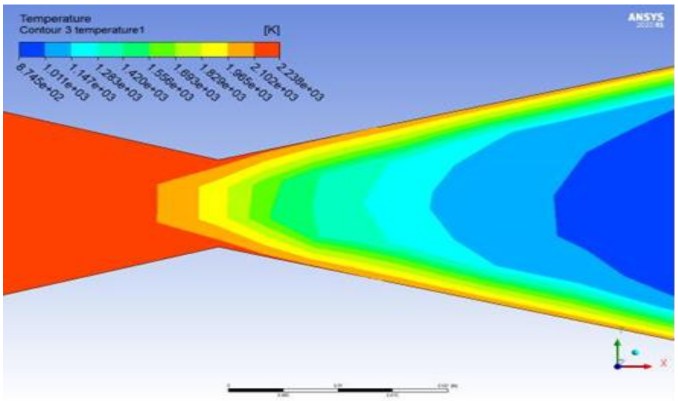

Fig -8: Temperature Variation at Mach 2.5

The minimum temperature of 8.745 e^02 K and the maximum temperature 2.238 e^03 K is experienced in the Single Inlet Rocket Nozzle at Mach 2.5.

Velocity Variation

The variations of velocity are shown.

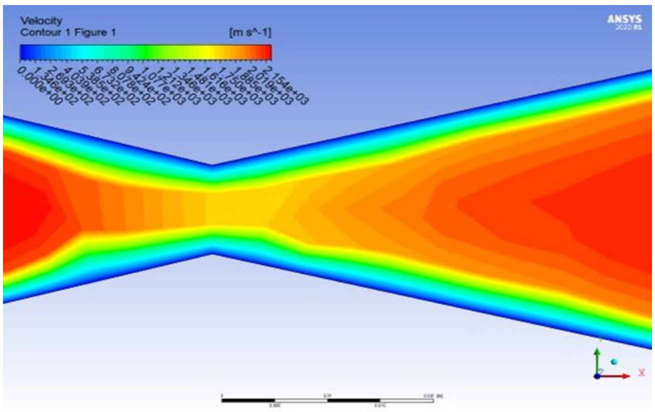

Fig -9: Velocity Variation at Mach 0.5

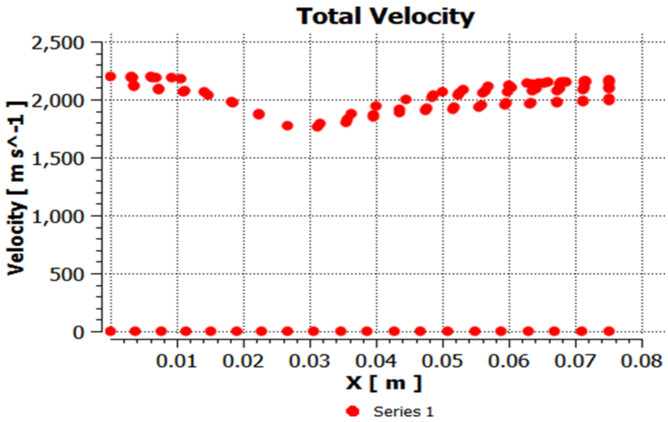

Chart -2: Velocity Variation at Mach 0.5

The minimum velocity 0 m/s and the maximum velocity of 2.154 e^03 m/s is experienced in the Single Inlet Rocket Nozzle at Mach 0.5.

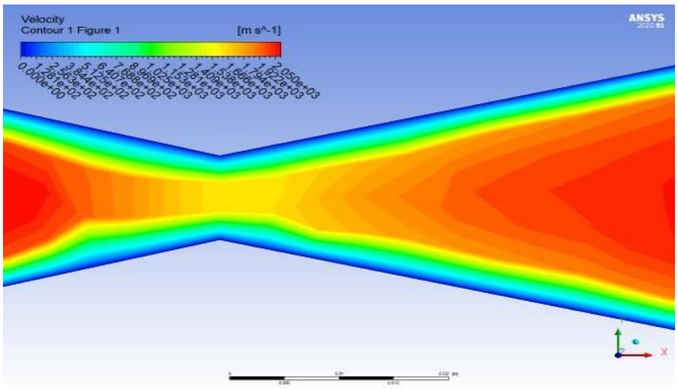

Fig -10: Velocity Variation at Mach 1

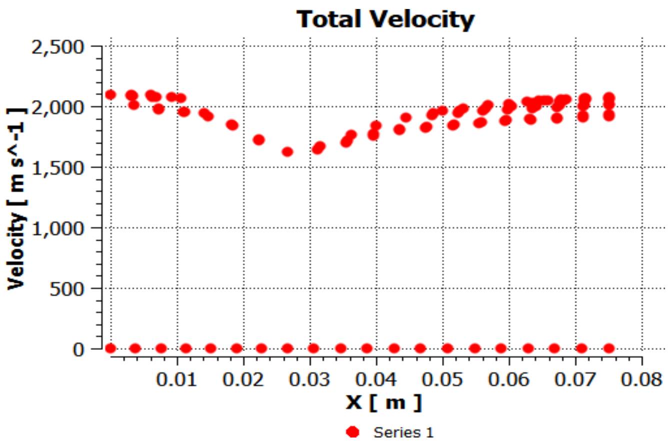

Chart -3: Velocity Variation at Mach 1

The minimum velocity 0 m/s and the maximum velocity of 2.05 e^03 m/s is experienced in the Single Inlet Rocket Nozzle at Mach 1.

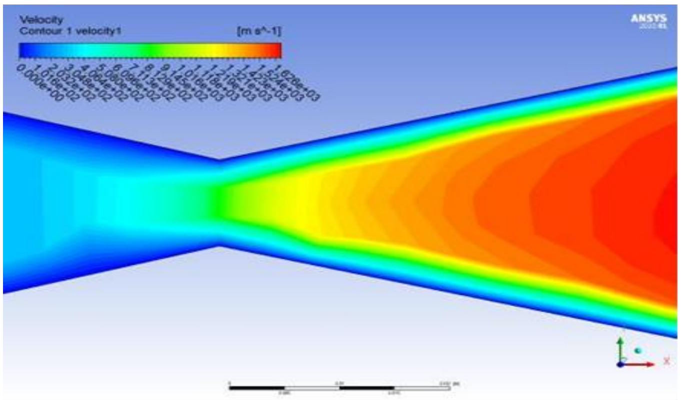

Fig -11: Velocity Variation at Mach 2.5

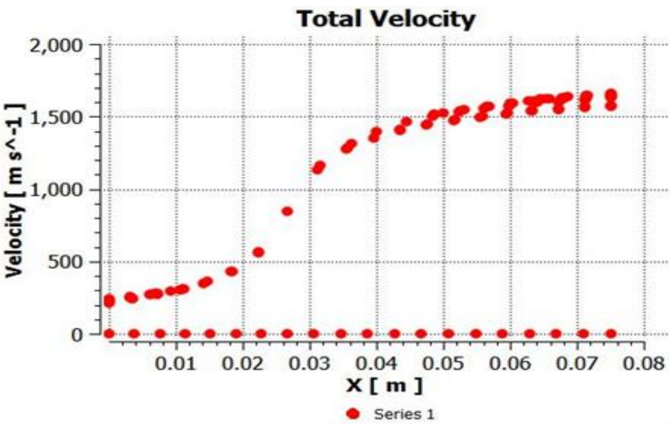

Chart -4: Velocity Variation at Mach 2.5

The minimum velocity of 0 m/s and the maximum velocity of 1.626 e^03 m/s is experienced in the Single Inlet Rocket Nozzle at Mach 2.5.

6.3 Solutions for Four Inlet Nozzle

Pressure Variation

The Combustion chamber pressure is taken to be 80 MPa, with a gas constant of 0.287 KJ/Kg-K. The output of the analysis is shown in the figure below.

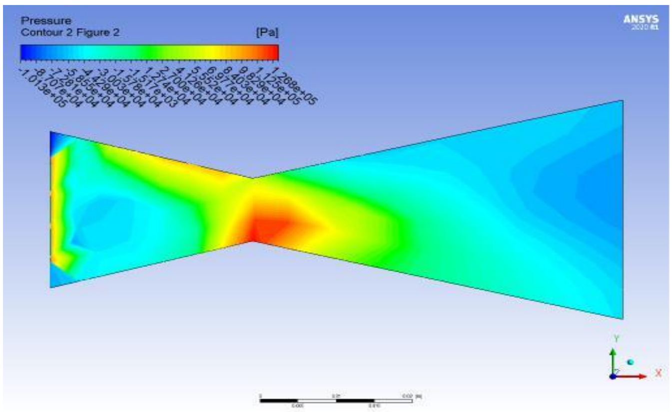

Fig -12: Pressure Variation at Mach 0.5

The minimum pressure -1.013e^05 Pa and the maximum pressure 1.268 e^05 Pa is experienced in the Four Inlet Rocket Nozzle at Mach 0.5.

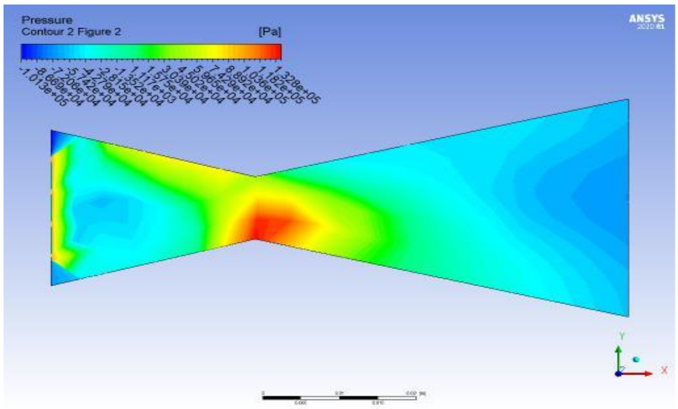

Fig -13: Pressure Variation at Mach 1

The minimum pressure -1.013e^05 Pa and the maximum pressure 1.328 e^05 Pa is experienced in the Four Inlet Rocket Nozzle at Mach 1.

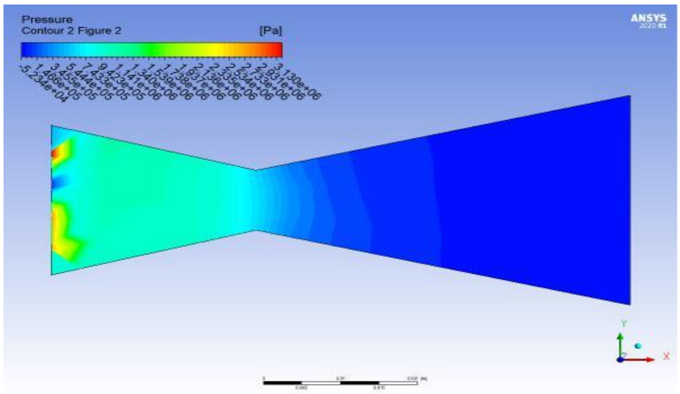

Fig -14: Pressure Variation at Mach 2.5

The minimum pressure -5.234 e^04 Pa and the maximum pressure 3.130 e^06 Pa is experienced in the Four Inlet Rocket Nozzle at Mach 2.5.

Temperature Variation

The Ideal temperature for a combustion chamber is taken as 3500K and the specific heat ratio as 1.2. The fluid considered is Air. The output of the analysis is shown below.

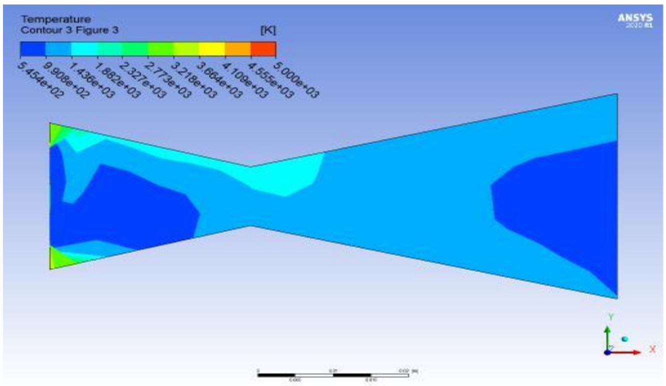

Fig -15: Temperature Variation at Mach 0.5

The minimum temperature of 5.454 e^02 K and the maximum temperature of 5.000e^03 K is experienced in the Four Inlet Rocket Nozzle at Mach 0.5.

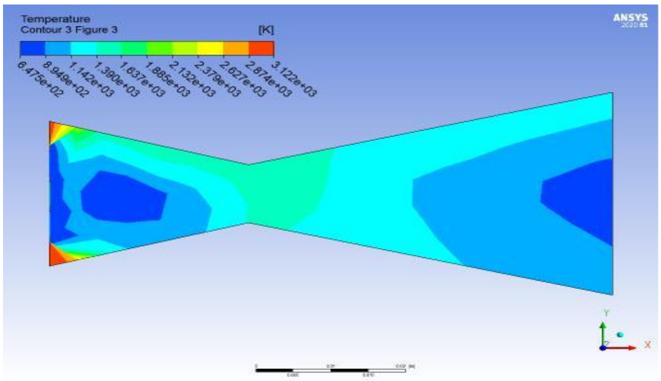

Fig -16: Temperature Variation at Mach 1

The minimum temperature of 6.475 e^02 K and the maximum temperature of 3.122e^03 K is experienced in the Four Inlet Rocket Nozzle at Mach 1.

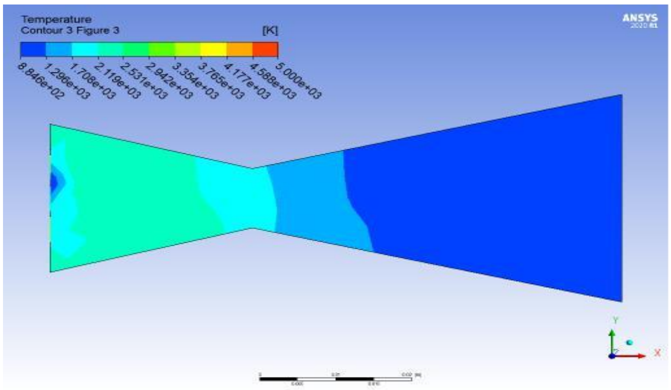

Fig -17: Temperature Variation at Mach 2.5

The minimum temperature of 8.846 e^02 K and the maximum temperature of 5.00 e^03 K is experienced in the Four Inlet Rocket Nozzle at Mach 2.5.

Velocity Variation

The variations of velocity are shown.

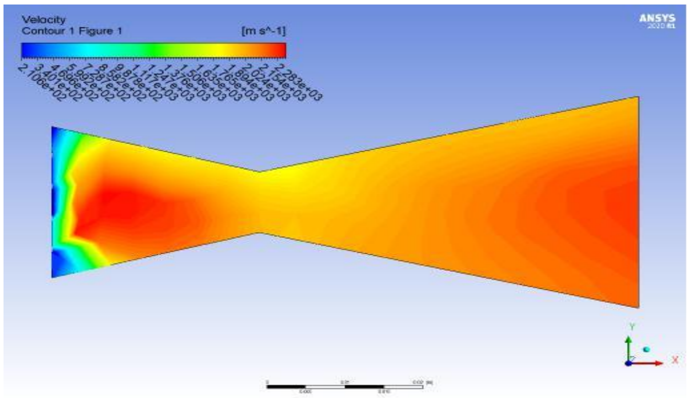

Fig -18: Velocity Variation at Mach 0.5

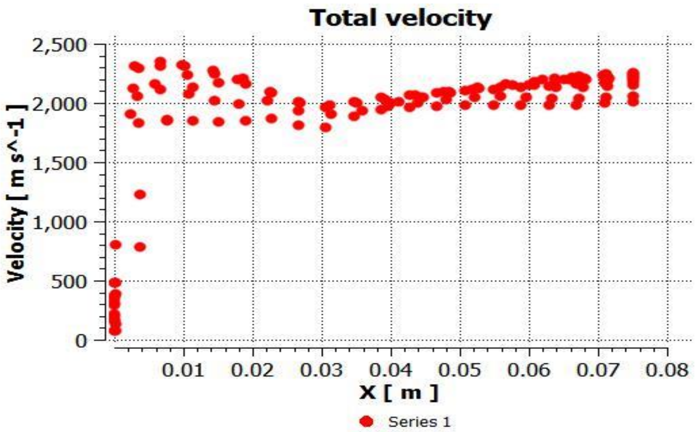

Chart -5: Velocity Variation at Mach 0.5

The minimum velocity of 2.106 e^02 m/s and the maximum velocity of 2.283 e^03 m/s is experienced in the Four Inlet Rocket Nozzle at Mach 0.5.

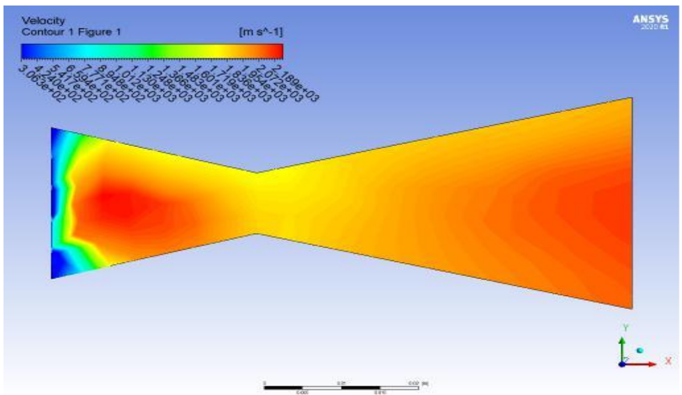

Fig -19: Velocity Variation at Mach 1

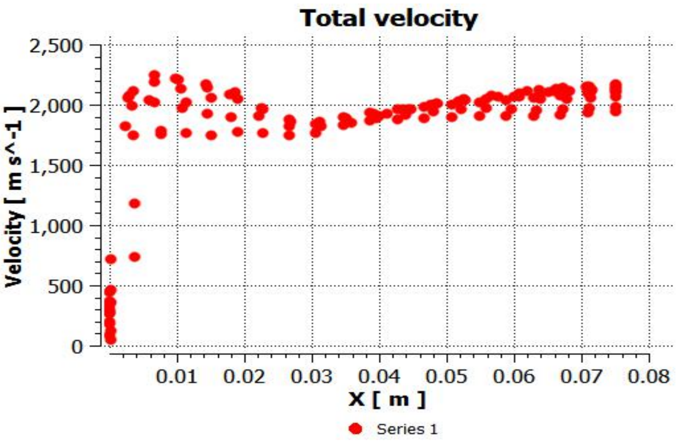

Chart -6: Velocity Variation at Mach 1

The minimum velocity of 3.063 e^02 m/s and the maximum velocity of 2.189 e^03 m/s is experienced in the Four Inlet Rocket Nozzle at Mach 1.

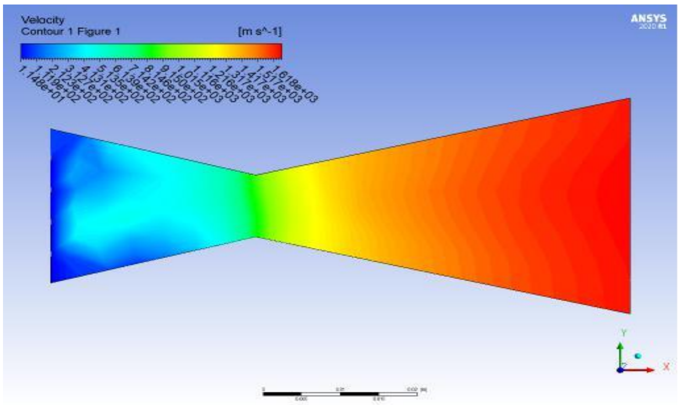

Fig -20: Velocity Variation at Mach 2.5

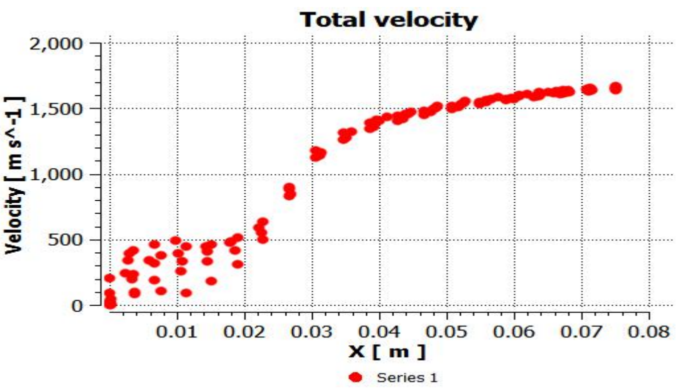

Chart -7: Velocity Variation at Mach 2.5

The minimum velocity is 1.148 e^01 m/s and the maximum velocity of 1.618 e^03 m/s is experienced in the Four Inlet Rocket Nozzle at Mach 2.5.

7. CONCLUSIONS

Nozzle models were developed considering the number of inlets to determine the pressure, temperature and velocity in them. The parameters were validated theoretically and computationally with numerical results found in the literature for both types of nozzles. The conclusion is drawn keeping note that, when the fuel and air are entering in the combustion chamber, its burn due to high velocity and temperature and then the temperature increases rapidly in the combustion chamber and convergent part of the nozzle and after that temperature decrease in the exit part of the nozzle.

8. FUTURE SCOPE

On comparing the theoretical and computational analysis results of the Rocket Nozzles, we can concur that the output of Four Inlet Nozzles, for all the parameters, i.e., temperature, pressure, and velocity, are higher than that of the Single Inlet Rocket Nozzle.

The maximum velocity output of the Four Inlet Nozzle is higher than that of the Single Inlet Rocket Nozzle, providing a higher take-off velocity, hence making it more preferable for use in Rockets.

The Four Inlet Rocket Nozzle in the supersonic zones tend to provide the highest pressure, temperature and velocity outputs, giving desirable values for the use in Rockets.

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