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CFD ANALYSIS OF CONVERGENT DIVERGENT ROCKET ENGINE NOZZLE

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ABSTRACT:

The primary motive of this project is to analyze a rocket engine nozzle for understanding the various design conditions under different convergent and divergent angles by Computational Fluid Dynamic (CFD), which is a branch of fluid mechanics that uses numerical analysis and data structures to solve and analyze problems that involve fluid flows. Computers are used to perform the calculations required to simulate the interaction of liquids and gases with surfaces defined by boundary conditions.For nozzles that are used in vacuum or at very high altitude, it is impossible to match ambient pressure; rather, nozzles with larger area ratio are usually more efficient. However, a very long nozzle has significant mass, a drawback in and of itself. A length that optimizes overall vehicle performance typically has to be found. Additionally, as the temperature of the gas in the nozzle decreases, some components of the exhaust gases (such as water vapor from the combustion process) may condense or even freeze. This is highly undesirable and needs to be avoided.The response of static pressure and Mach number values of CFD analysis for the varying combinations of the convergent and divergent angles of the nozzle are observed. The analysis is carried out for obtaining the optimal results for the given combination.

Key words: Convergent Divergent Nozzle, Computational Fluid Dynamics, Mach Number, Static Pressure, Ansys, Hyper mesh etc.

I.INTRODUCTION

A rocket engine uses a nozzle to accelerate hot exhaust to produce thrust as described by Newton's third law of motion. The amount of thrust produced by the engine depends on the mass flow rate through the engine, the exit velocity of the flow, and the pressure at the exit of the engine. The value of these three flow variables are all determined by the rocket

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nozzle design.A nozzle is a relatively simple device, just a specially shaped tube through which hot gases flow. Rockets typically use a fixed convergent section followed by a fixed divergent section for the design of the nozzle. This nozzle configuration is called a convergent-divergent, or CD, nozzle. In a CD rocket nozzle, the hot exhaust leaves the combustion chamber and converges down to the minimum area, or throat, of the nozzle. The throat size is chosen to choke the flow and set the mass flow rate through the system. The flow in the throat is sonic which means the Mach number is equal to one in the throat. Downstream of the throat, the geometry diverges and the flow is isentropic ally expanded to a supersonic Mach number that depends on the area ratio of the exit to the throat. The expansion of a supersonic flow causes the static pressure and temperature to decrease from the throat to the exit, so the amount of the expansion also determines the exit pressure and temperature. The exit temperature determines the exit speed of sound, which determines the exit velocity. The exit velocity, pressure, and mass flow through the nozzle determine the amount of thrust produced by the nozzle.

For nozzles that are used in vacuum or at very high altitude, it is impossible to match ambient pressure; rather, nozzles with larger area ratio are usually more efficient. However, a very long nozzle has significant mass, a drawback in and of itself. A length that optimizes overall vehicle performance typically has to be found. Additionally, as the temperature of the gas in the nozzle decreases, some components of the exhaust gases (such as water vapor from the combustion process) may condense or even freeze. This is highly undesirable and needs to be avoided.

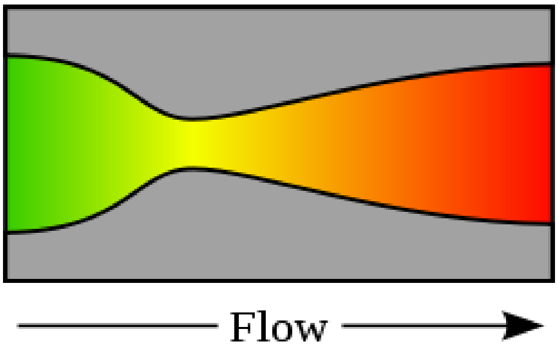

Figure-1: A De Laval Nozzle, Showing approximate Flow Velocity increasing from Green to Red in the direction of Flow

II.NOZZLE DESIGN IN ANSYS

Generating Geometry:

1. Create one temporary node in Geometry panel. Geometry → Nodes → XYZ panel and create.
2. Create four circles in Geometry panel. Geometry → Lines → Circle center and Radius and enter the radius of circle as per the dimensions.
3. Create surface using Ruled option. 2D → Ruled and select two lines.
4. Generate Solid by using the surfaces. Geometry → Solids → Bounding Surfac and select surfaces.

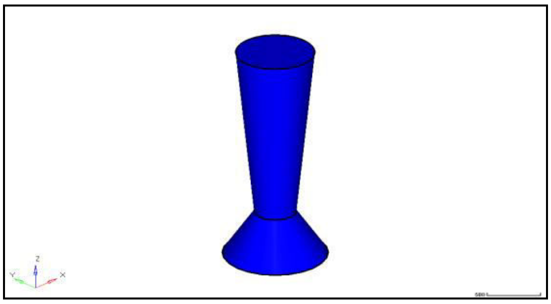

Figure-2: Nozzle Design in Ansys in 3-D

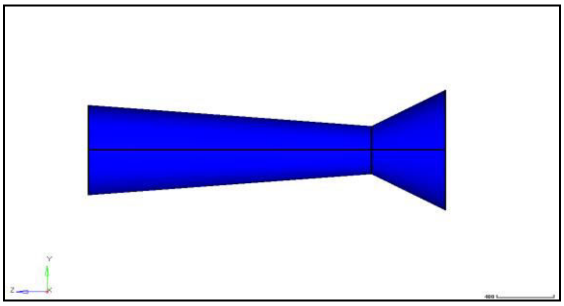

Figure 3: Design of Nozzle in Ansys in XY-Direction

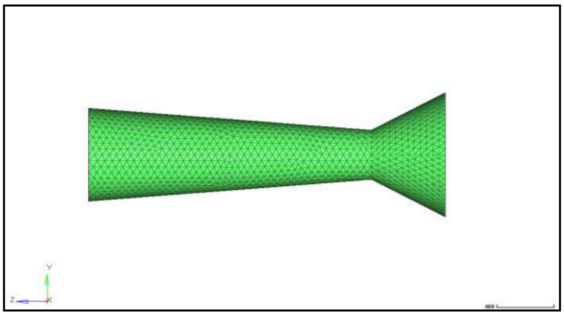

Figure-4: Meshing of CD Nozzle

III. CFD ANALYSIS OF CD ROCKET NOZZLE

In the following project a 3D geometry and mesh is generated and imported in Ansys Workbench. The CFX domain is used as the CFD tool for the purpose of solving. The nozzle having an inlet radius of 500mm, throat radius of 200mm and the exit diameter of 375mm was considered for analysis. The inlet parameters considered are total pressure of 4.22 MPa and total temperature of 3127 °C .The convergent and divergent angles are considered as the optimization parameters for the design of the rocket nozzle. A combination of the convergent angles of 30°, 45° and divergent angles of 5°, 7°are as mentioned below in the table-1.

Convergent Angle (deg)	Divergent Angle (deg)
30	5
30	7
45	5
45	7

CALCULATIONS:-

Convergent – divergent rocket nozzle angle at 30^0 and 5^0

Given data:-

Convergent diameter (Di) = 1m

Throat diameter (D_T) = 0.4m

Divergent diameter,(D_D) = 0.75m

Total pressure,(P) = 42.2bar

Total Temperature,(T) = 3673^0 K

Convergent angle,(β) = 30^0

Divergent angle,(θ) = 5^0

Throat angle,(R) = 0^0

Exit mach number,(M) = ?

Exit static pressure, (P) = ?

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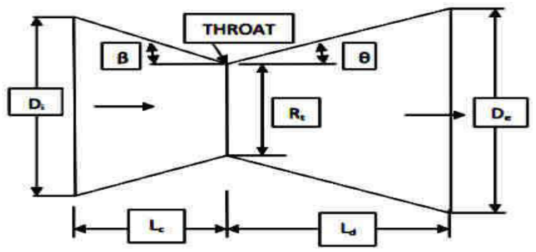

Figure-5: CD Nozzle

EXIT MACH NUMBER :-

MACH NUMBER, (M)= $\frac{\text{EXIT VELOCITY}}{\text{VELOCITY OF SOUND}}$

=

Velocity of sound, (C)= $\sqrt{\Upsilon RT}$

Taking values

Specific gas constant, R = 0.287 KJ/kg ^{0}K

Υ = 1.4

C = $\sqrt{1.4x0.287x3673}$ = 38.14 m/s

THROAT VELOCITY:-

$$V_T = \sqrt{\frac{2\Upsilon}{\Upsilon+1} P_I V_I \left[1 - \frac{P_T}{P_I}\right]^{\frac{\Upsilon-1}{\Upsilon}}}$$

Where

P_I = Initial Pressure (or) Entrance Pressure

P_T = Throat pressure

P_E = Exit Pressure (or) Final Pressure

Initial pressure P_I = ρRT

Where

air density (ρ) = 1.2256

R = 0.287 KJ/kg^{0}K

P_I = 1.2256x0.287x3673

= 12.9x10^5 N/m^2 **Throat pressure, P_T**

$$\frac{P_T}{P_I} = \left[\frac{2}{\Upsilon+1}\right]^{\frac{\Upsilon}{\Upsilon-1}}$$

$$P_T = \left[\frac{2}{1.4+1}\right]^{\frac{1.4}{1.4-1}} x\ P_I$$

P_T = 6.81 bar

Initial pressure(P_I) = 12.9bar

Throat pressure (P_T) = 6.81bar

Final pressure (P_E) = 0.42bar

$$V_T = \sqrt{\frac{2\Upsilon}{\Upsilon+1} P_I V_I \left[1 - \frac{P_T}{P_I}\right]^{\frac{\Upsilon-1}{\Upsilon}}}$$

$$V_T = \sqrt{7x1054[1 - 0.52]^{\frac{0.4}{1.4}}}$$

= 136.3 m/s

EXIT VELOCITY:-

$$V_E = \sqrt{\frac{2\Upsilon}{\Upsilon+1} P_I V_I \left[1 - \frac{P_E}{P_I}\right]^{\frac{\Upsilon-1}{\Upsilon}}} = = 136\text{m/s}$$

Therefore, M = $\frac{136}{38.41}$ = 3.54

STATIC PRESSURE (P_a):-

$$\frac{P_a}{P} = \left[1 + \left[\frac{\Upsilon+1}{2}\right] M^2\right]^{\frac{\Upsilon}{\Upsilon-1}}$$

P_a = 100326 N/m^2

Similarly,

Case-II: Convergent – divergent rocket nozzle angle at 30^0 and 7^0

M = 2.265; P_a = 256459 N/m^2

Case-III: Convergent – divergent rocket nozzle angle at 45^0 and 5^0

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M = 2.26365; P_a = 245444 N/m^2

Case-IV: Convergent – divergent rocket nozzle angle at 45^0 and 7^0

M = 2.25428; P_a = 251132 N/m^2

IV.RESULTS

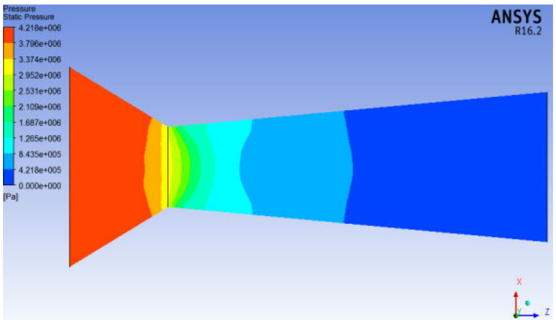

Figure-6:Static Pressure (Convergent Angle = 30°, Divergent Angle = 5°)

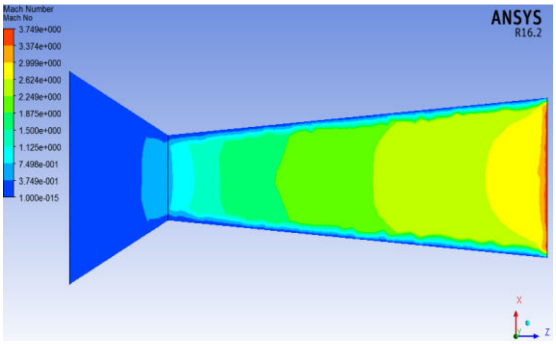

Figure-7: Mach Number (Convergent Angle = 30°, Divergent Angle = 5°)

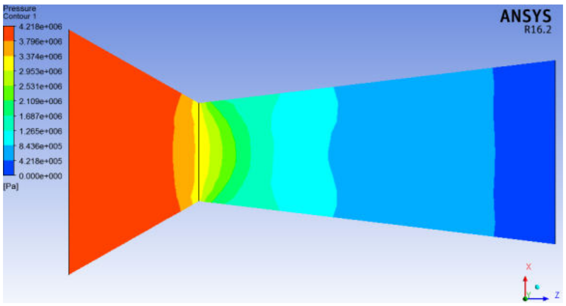

Figure-8 : Static Pressure (Convergent Angle = 30°, Divergent Angle = 7°)

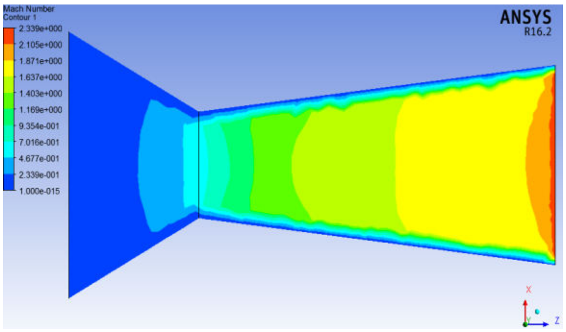

Figure-9: Mach Number (Convergent Angle = 30°, Divergent Angle = 7°)

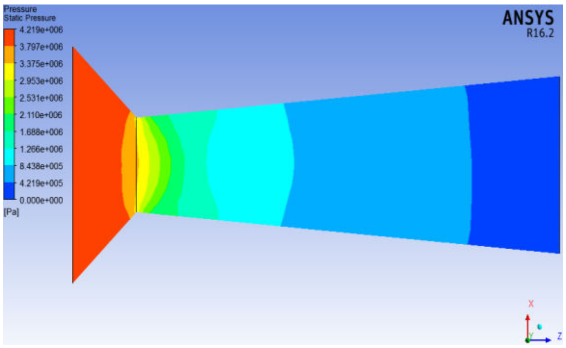

Figure-10: Static Pressure (Convergent Angle = 45°, Divergent Angle = 5°)

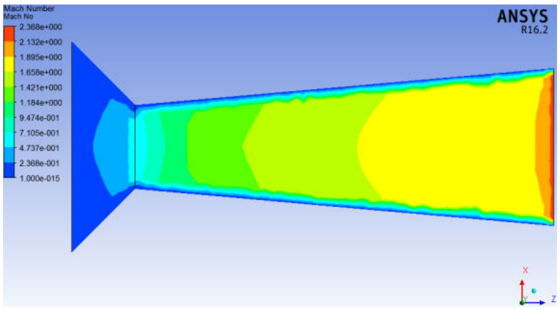

Figure-11: Mach Number (Convergent Angle = 45°, Divergent Angle = 5°)

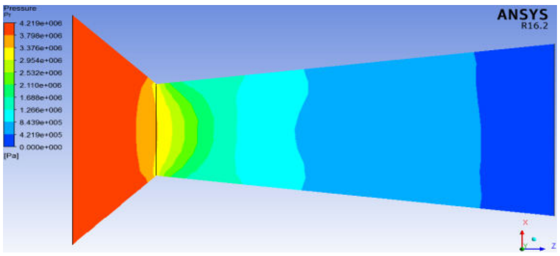

Figure-12:Static Pressure (Convergent Angle = 245°, Divergent Angle = 7°)

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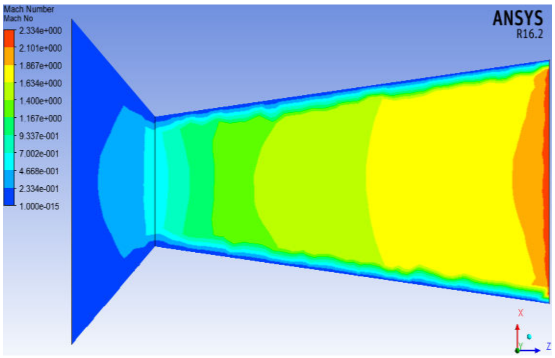

Figure-13: Mach Number (Convergent Angle = 45°, Divergent Angle = 7°)

Table-2: Summary of results

S. No	Convergent Angle (Degree)	Divergent Angle (Degree)	Exit Static Pressure (Pa)	Exit Mach Number
1	30	5	100326	3.53924
2	30	7	256459	2.25128
3	45	5	245444	2.26365
4	45	7	251132	2.25428

V.CONCLUSION

The values of the static pressure and Mach number at the exit depend on the convergent and divergent angles of the rocket nozzle. Increase in divergent angle increases the exit pressure whereas increasing the convergent angle decreases the exit pressure. The maximum static pressure for the considered combinations is observed for 30° convergent and 7° divergent angles. It can be clearly observed from the results that decreasing the convergent as well as divergent angles will increase the Mach number. The highest of all Mach numbers as per the analysis is obtained at 30° convergent and 5° divergent angles. To have a proposed motion even though there is decrease in mach number (**2.25128**), static pressure (**256459 Pa**) is at more 30 ^{0} convergent and 7 ^{0} divergent which is the optimal solution.

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