CFD Analysis on a Different Advanced Rocket Nozzles

Munipally Prathibha, M. Satyanarayana Gupta, Simhachalam Naidu

Abstract*— *The reduction of Earth-to-orbit launch costs in conjunction with an increase in launcher reliability and operational Efficiency is the key demands on future space transportation systems, like single-stage-to-orbit vehicles (SSTO). The realization of these vehicles strongly depends on the performance of the engines, which should deliver high performance with low system complexity. Performance data for rocket engines are practically always lower than the theoretically attainable values because of imperfections in the mixing, combustion, and expansion of the propellants. The main part of the project addresses different nozzle concepts with improvements in performance as compared to conventional nozzles achieved by Different Mach numbers, thus, by minimizing losses caused by over- or under expansion. The design of different nozzle shapes and flow simulation is done in gambit and fluent software's respectively for various parameters

Keywords: launcher reliability, future space transportation systems, theoretically attainable, mixing, combustion, and expansion.

I. INTRODUCTION

A nozzle is a device designed to control the direction or characteristics of a fluid flow (especially to increase velocity) as it exits (or enters) an enclosed chamber. A nozzle is often a pipe or tube of varying cross sectional area and it can be used to direct or modify the flow of a fluid (liquid or gas). Nozzles are frequently used to control the rate of flow, speed, direction, mass, shape, and/or the pressure of the stream that emerges from them. A jet exhaust produces a net thrust from the energy obtained from combusting fuel which is added to the inducted air. This hot air is passed through a high speed nozzle, a propelling nozzle which enormously increases its kinetic energy. The goal of nozzle is to increase the kinetic energy of the flowing medium at the expense of its pressure and internal energy. Nozzles can be described as convergent (narrowing down from a wide diameter to a smaller diameter in the direction of the flow) or divergent (expanding from a smaller diameter to a larger one). A de Laval nozzle has a convergent section followed by a divergent section and is often called a convergent-divergent nozzle ("con-di nozzle"). Convergent nozzles accelerate subsonic fluids. If the nozzle pressure ratio is high enough the flow will reach sonic velocity at the narrowest point (i.e. the nozzle throat). In this situation, the nozzle is said to be choked.

Increasing the nozzle pressure ratio further will not increase the throat Mach number beyond unity. Downstream (i.e. external to the nozzle) the flow is free to expand to supersonic velocities. Note that the Mach 1 can be a very high speed for a hot gas; since the speed of sound varies as the square root of absolute temperature. Thus the speed reached at a nozzle throat can be far higher than the speed of sound at sea level. This fact is used extensively in rocketry where hypersonic flows are required, and where propellant mixtures are deliberately chosen to further increase the sonic speed. Divergent nozzles slow fluids, if the flow is subsonic, but accelerate sonic or supersonic fluids. Convergent-divergent nozzles can therefore accelerate fluids that have choked in the convergent section to supersonic speeds. This CD process is more efficient than allowing a convergent nozzle to expand supersonically externally. The shape of the divergent section also ensures that the direction of the escaping gases is directly backwards, as any sideways component would not contribute to thrust.

II. NOZZLES BASIC REVIEW

A rocket nozzle includes three main elements: a converging section, a throat, and a diverging section. The combustion exhaust gas first enters the converging section. The gas moves at subsonic speeds through this area, accelerating as the cross sectional area decreases. In order to reach supersonic speeds, the gas must first pass through an area of minimum cross sectional area called the throat. From here, the supersonic gas expands through the converging section and then out of the nozzle. Supersonic flow accelerates as it expands.

The following are the features of nozzle,

• Nozzle produces thrust.

• Convert thermal energy of hot chamber gases into kinetic energy and direct that energy along nozzle axis.

• Exhaust gases from combustion are pushed into throat region of nozzle.

• Throat is smaller cross-sectional area than rest of engine; here gases are compressed to high pressure.

• Nozzle gradually increases in cross-sectional area allowing gases to expand and push
against walls creating thrust.

• Mathematically, ultimate purpose of nozzle is to expand gases as efficiently as possible so as to maximize exit velocity.

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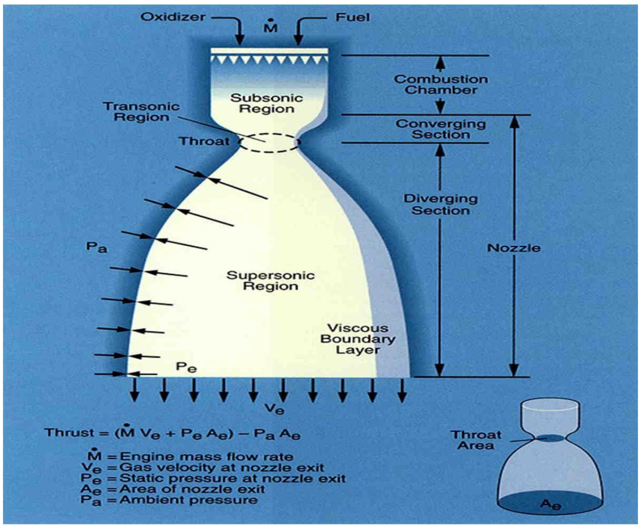

Fig. 1.1 Nozzle sections

• EXPANSION AREA RATIO

Most important parameter in nozzle design is expansion area ratio, e. Fixing other variables (primarily chamber pressure) → only one ratio that optimizes performance for a given altitude (or ambient pressure).

However, we have to keep in mind that rocket does not travel at only one altitude, so we should know trajectory to select expansion ratio that maximizes performance over a range of ambient pressures. Thus variable expansion ratio nozzles are preferred for space travel.

III. WHY NOZZLES ARE USED?

Nozzles are frequently used to control the rate of flow, speed, direction, mass, shape, and/or the pressure of the stream that emerges from them. A jet exhaust produces a net thrust from the energy obtained from combusting fuel which is added to the inducted air. This hot air is passed through a high speed nozzle, a propelling nozzle which enormously increases its kinetic energy.The goal of nozzle is to increase the kinetic energy of the flowing medium at the expense of its pressure and internal energy. Convergent nozzles accelerate subsonic fluids. If the nozzle pressure ratio is high enough the flow will reach sonic velocity at the narrowest point (i.e. the nozzle throat).Convergent nozzles accelerate subsonic fluids. If the nozzle pressure ratio is high enough the flow will reach sonic velocity at the narrowest point (i.e. the nozzle throat).

IV. WORKING OF ROCKET

A rocket engine, or simply "rocket", is a jet engine that uses only stored propellant mass for forming its high speed propulsive jet. Rocket engines are reaction engines and obtain thrust in accordance with Newton's third law. Since, they need no external material to form their jet, rocket engines can be used for spacecraft propulsion as well as terrestrial uses, such as missiles. Most rocket engines are internal combustion engines, although non-combusting forms also exist. Rocket engines as a group have the highest exhaust velocities, are by far the lightest, but are the least propellant efficient of all types of jet engines. Rocket technology can combine high thrust (mega Newton’s), very high exhaust speeds (around 10 times the speed of sound in air at sea level) and very high thrust/weight ratios (>100) simultaneously as well as being able to operate outside the atmosphere, and while permitting the use of low pressure and hence lightweight tanks and structure.

V. PRINCIPLE OF OPERATION

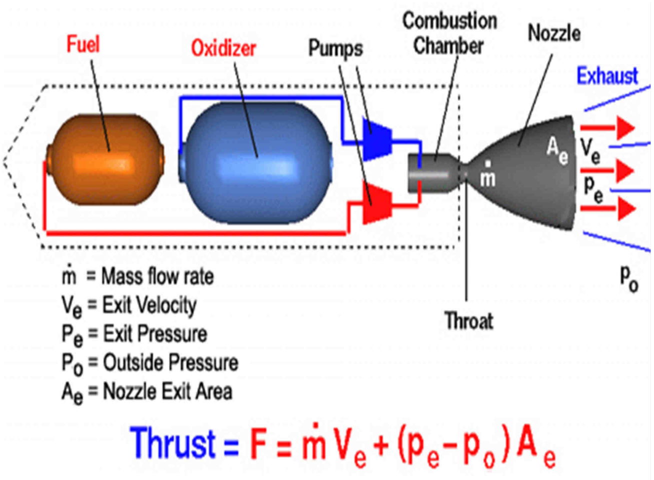

Fig. 1.2 Principle of Rocket

Rocket engines produce thrust by the expulsion of a high-speed fluid exhaust. This fluid is nearly always a gas which is created by high pressure (10-200 bar) combustion of solid or liquid propellants, consisting of fuel and oxidizer components, within a combustion chamber. The fluid exhaust is then passed through a supersonic propelling nozzle which uses heat energy of the gas to accelerate the exhaust to very high speed, and the reaction to this pushes the engine in the opposite direction. In rocket engines, high temperatures and pressures are highly desirable for good performance as this permits a longer nozzle to be fitted to the engine, which gives higher exhaust speeds, as well as giving better thermodynamic efficiency. Below is an approximate equation for calculating the net thrust of a rocket engine:

$$F_n = \dot{m}\, v_e = \dot{m}\, v_{e-act} + A_e(p_e - p_{amb})$$

Where:

$\dot{m}$ = exhaust gas mass flow

v_e = effective exhaust velocity

v_{e-act} = actual jet velocity at nozzle exit plane

A_e = flow area at nozzle exit plane (or the plane where the jet leaves the nozzle if separated flow)

p_e = static pressure at nozzle exit plane

p_{amb} = ambient (or atmospheric) pressure

Since, unlike a jet engine, a conventional rocket motor lacks an air intake, there is no 'ram drag' to deduct from the gross thrust. Consequently the net thrust of a rocket motor is equal to the gross thrust (apart from static back pressure). The $\dot{m}\ v_{e-act}$ term represents the momentum thrust, which remains constant at a given throttle setting, whereas the $A_e(p_e - p_{amb})$ term represents the pressure thrust term. At full throttle, the net thrust of a rocket motor improves slightly with increasing altitude, because as atmospheric pressure decreases with altitude, the pressure thrust term increases. At the surface of the Earth the pressure thrust may be reduced by up to 30%, depending on the engine design. This reduction drops roughly exponentially to zero with increasing altitude. Maximum thrust for a rocket engine is achieved by maximizing the momentum contribution of the equation without incurring penalties from over expanding the

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exhaust. This occurs when $p_{e} = p_{amb}$. Since ambient pressure changes with altitude, most rocket engines spend very little time operating at peak efficiency.

VI. Role of Nozzle in Rocket

For optimal performance the pressure of the gas at the end of the nozzle should just equal the ambient pressure: if the exhaust's pressure is lower than the ambient pressure, then the vehicle will be slowed by the difference in pressure between the top of the engine and the exit; on the other hand, if the exhaust's pressure is higher, then exhaust pressure that could have been converted into thrust is not converted, and energy is wasted.To maintain this ideal of equality between the exhaust's exit pressure and the ambient pressure, the diameter of the nozzle would need to increase with altitude, giving the pressure a longer nozzle to act on (and reducing the exit pressure and temperature). This increase is difficult to arrange in a lightweight fashion, although is routinely done with other forms of jet engines. In rocketry a lightweight compromise nozzle is generally used and some reduction in atmospheric performance occurs when used at other than the 'design altitude' or when throttled. To improve on this, various exotic nozzle designs such as the plug nozzle, stepped nozzles, the expanding nozzle and the aero spike have been proposed, each providing some way to adapt to changing ambient air pressure and each allowing the gas to expand further against the nozzle, giving extra thrust at higher altitudes. When exhausting into a sufficiently low ambient pressure (vacuum) several issues arise. One is the sheer weight of the nozzle—beyond a certain point, for a particular vehicle, the extra weight of the nozzle outweighs any performance gained. Secondly, as the exhaust gases adiabatically expand within the nozzle they cool and eventually some of the chemicals can freeze, producing 'snow' within the jet. This causes instabilities in the jet and must be avoided. On a De Laval nozzle, exhaust gas flow detachment will occur in a grossly over-expanded nozzle. As the detachment point will not be uniform around the axis of the engine, a side force may be imparted to the engine. This side force may change over time and result in control problems with the launch vehicle.

VII. Types of Nozzles

Types of nozzles are several types. They could be based on either speed or shape.

a. Based on speed

The basic types of nozzles can be differentiated as

- Spray nozzles
- Ramjet nozzles

b. Based on shape

The basic types of nozzles can be differentiated as

- Conical
- Bell
- Annular

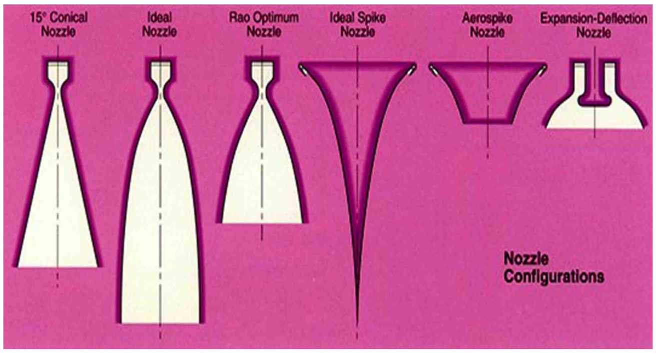

Fig. 1.3 Types of nozzles

CONICAL NOZZLES:

• Used in early rocket applications because of simplicity and ease of construction

• Cone gets its name from the fact that the walls diverge at a constant angle

• A small angle produces greater thrust, because it maximizes the axial component of exit velocity and produces a high specific impulse

• Penalty is longer and heavier nozzle that is more complex to build

• At the other extreme, size and weight are minimized by a large nozzle wall angle

– Large angles reduce performance at low altitude because high ambient pressure causes overexpansion and flow separation

• Primary Metric of Characterization: Divergence Loss

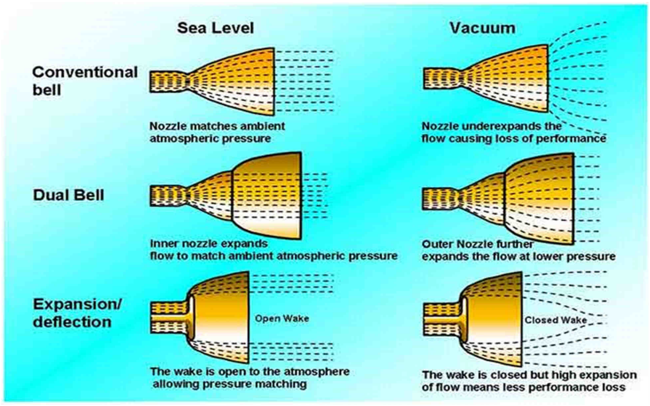

Fig. 1.4 Comparison of nozzles at sea level and Vacuum

BELL and Dual Bell:

This nozzle concept was studied at the Jet Propulsion Laboratory in 1949. In the late 1960s, Rocket dyne patented this nozzle concept, which has received attention in recent years in the U.S. and Europe. The design of this nozzle concept with its typical inner base nozzle, the wall in section, and the outer nozzle extension can be seen. This nozzle concept offers an altitude adaptation achieved only by nozzle wall in section. In flow altitudes, controlled and symmetrical flow separation occurs at this wall in section, which results in a lower effective area ratio. For higher altitudes, the nozzle flow is attached to the wall until the exit plane, and the full geometrical area ratio is used. Because of the higher area ratio, an improved vacuum performance is achieved. However, additional performance losses are induced in dual-bell nozzles.

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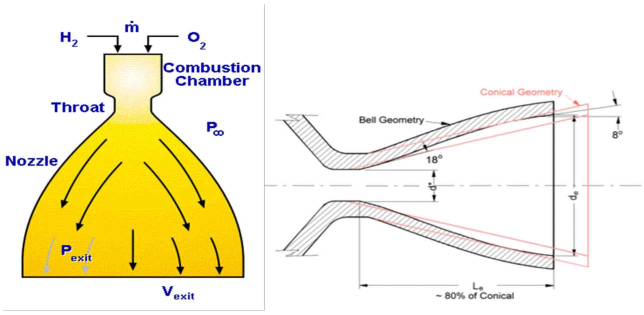

Fig. 1.5 Bell Nozzle

Annular Nozzle:

- Annular (plug or altitude-compensating) nozzle
  - – Least employed due to greater complexity, actually be best in theory
  - – Annular: combustion occurs along ring, or annulus, around base of nozzle
  - – Plug: refers to center body that blocks flow from what would be center portion of traditional nozzle
  - – Primary advantage: Altitude-compensation
- Another parameter annular diameter ratio, D_{plug} / D_{throat}
  - – Ratio is used as a measure of nozzle geometry for comparison with other plug nozzle shapes
- Two major types of annular nozzles have been developed to date
- Distinguished by method in which they expand exhaust: (1) outward or (2) inward

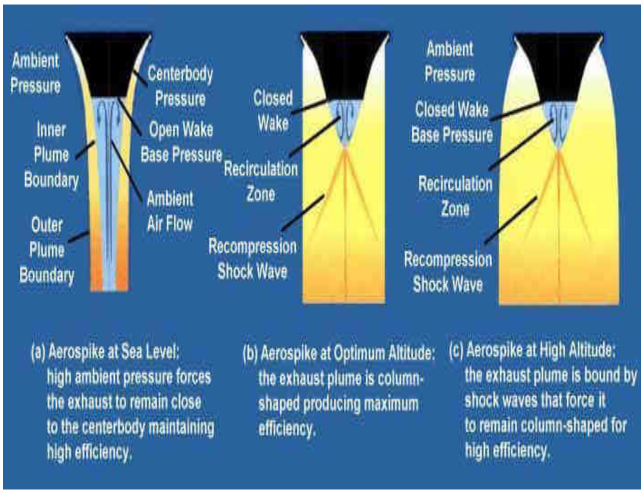

Fig. 1.6 Altitude compensation-Annular

VIII. How Nozzles Are Designed?

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 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 isentropically 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.

IX. Different Types of Software Used

We use variety of software to make our work easy, fast and accurate. The software required will be on two categories. They are designing and analysis. Recently we have many types of software for designing. We mainly use three types of software. They are

- CATIA
- Gambit
- ANSYS

X. Dimensions and Boundary Conditions Assumed

Inlet diameter	69
Exit diameter	82
Inlet pressure	210000
Temperature	300k

Table 1.1: CD Nozzle dimensions and boundary conditions

Inlet diameter	48
Exit diameter	68
Inlet pressure	210000
Total temperature	300k

Table 1.2: Bell Nozzle dimensions and boundary conditions

Inlet diameter	48
Exit diameter	91
Inlet pressure	210000
Total temperature	300k

Table 1.3: Double bell Nozzle dimensions and boundary conditions

Inlet diameter	69
Exit diameter	100
Inlet pressure	210000
Total temperature	300k

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Table 1.4: Expandable Nozzle dimensions and boundary conditions

B. Procedure to be followed

- Plotting key points

First we need to create key points by using the coordinate points.

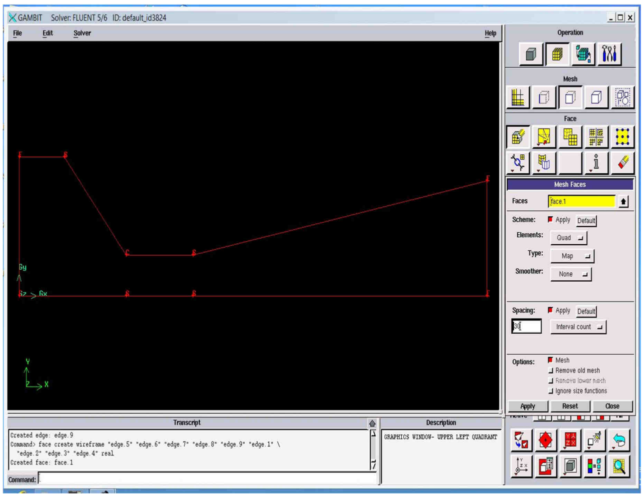

Fig. 1.7 Plotting key points

- Making edges

Then we need to create the edges. The edges can be joined by using the key points. Every key point has to be joined in order. Edges formed will be represented in red color.

- Making faces

Then we need to create the faces.The faces created will now change from red color to blue color. We can also convert the faces to volumes if there is a closed edge. Then the color will change to green color.

- Meshing:

Then we need to mesh the faces.

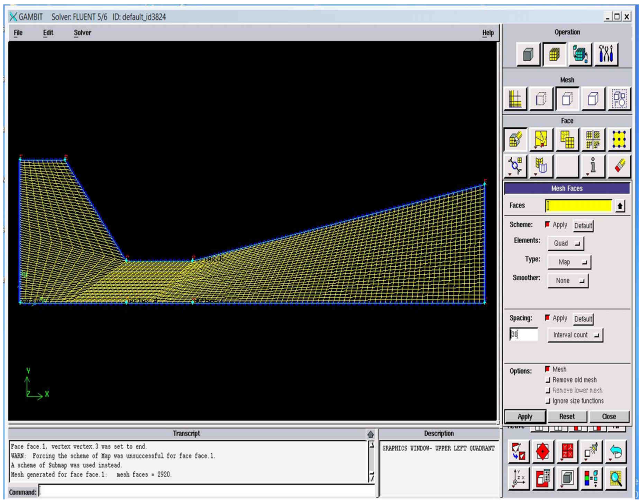

Fig. 1.8 Applying Boundary conditions

- Applying Boundary conditions

Applying boundary conditions indicate that we need to give boundary conditions to each and every face. For example, the inlet has to be given certain conditions like inlet pressure and inlet temperature. Likewise we need to give wall boundary conditions to the top surface. Similarly axis condition should be given to the axis.

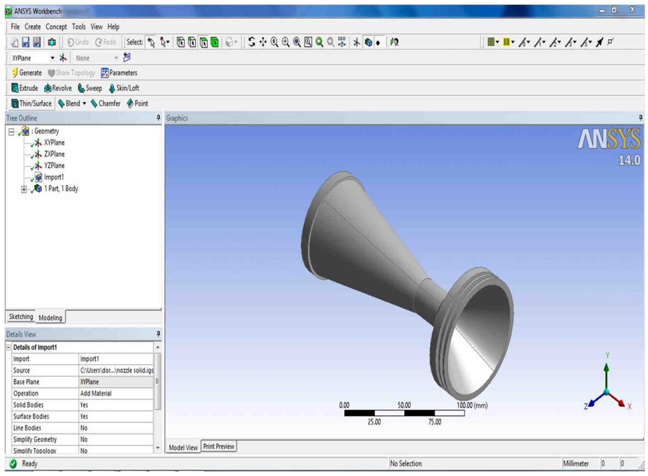

Fig. 1.9 3D view of model in ANSYS workbench

XI. THE CFD RESULTS

The CFD analysis of a rocket engine nozzle has been conducted to understand the phenomena of subsonic flow through it at various divergent angles. A two -dimensional axisymmetric model is used for the analysis and the governing equations were solved using the finite-volume method in ANSYS FLUENT® software. The variations in the parameters like the Mach number, static pressure, turbulent intensity are being analyzed. The phenomena of oblique shock are visualized and the travel of shock with divergence angle is visualized. Computational Fluid Dynamics (CFD) is an engineering tool that assists experimentation. Its scope is not limited to fluid dynamics; CFD could be applied to any process which involves transport phenomena with it. To solve an engineering problem we can make use of various methods like the analytical method, experimental methods using prototypes. The analytical method is very complicated and difficult. The experimental methods are very costly. If any errors in the design were detected during the prototype testing, another prototype is to be made clarifying all the errors and again tested. This is a time-consuming as well as a costconsuming process. Flow instabilities might be created inside the nozzle due to the formation if shocks which reduce the exit Mach number as well as thrust of the engine. This could be eliminated by varying the divergent angle. Here analysis has been conducted on nozzles with divergent angles and thus change in the external diameter 32, 34, 40, 44, 50, 55. Experimentation using the prototypes of each divergent angle is a costly as well as a time consuming process. CFD proves to be an efficient tool to overcome these limitations. Here in this work the trend of various flow parameters are also analyzed.

a. CD Nozzle results:

i) Density:

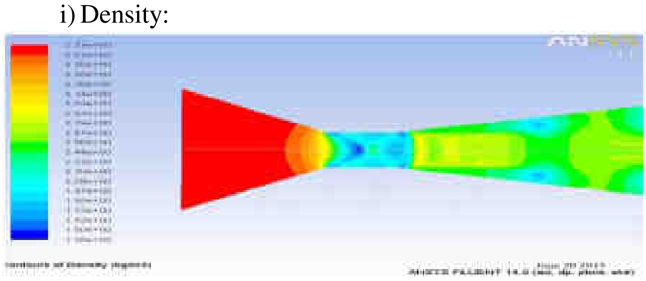

Fig. 1.10: contours of density

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ii) Axial velocity

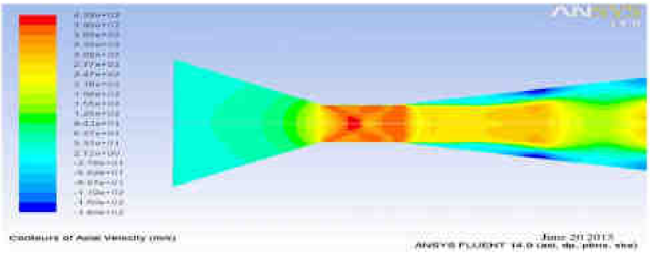

Fig. 1.11: contours of axial velocity

iii) Mach number

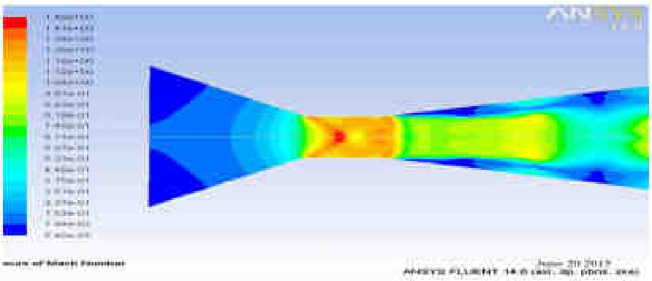

Fig. 1.12: contours of mach number

iv) Mach vector

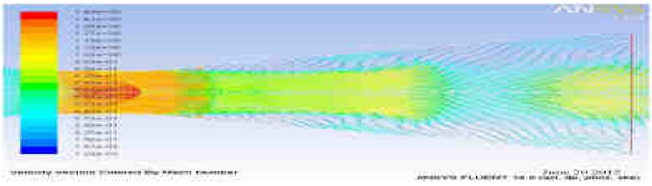

Fig. 1.13: velocity vectors colored by mach number

v) Pressure

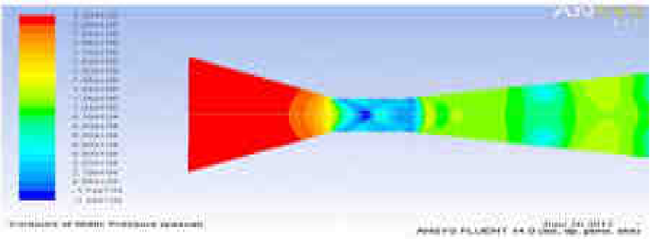

Fig. 1.14: contours of static pressure

vi) Radial velocity

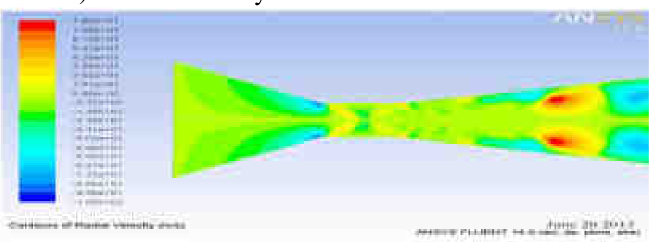

Fig. 1.15: contours of radial velocity

vii) Velocity

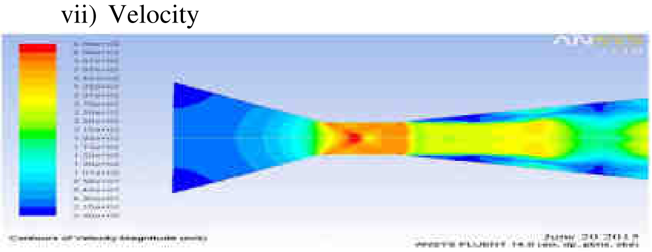

Fig. 1.16 contours of velocity magnitude

viii) Velocity vector

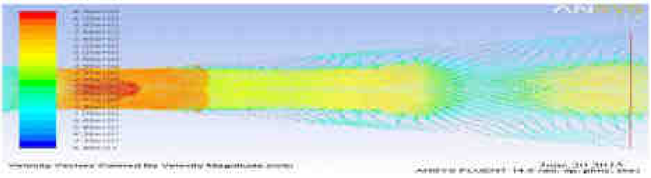

Fig. 1.17: velocity vectors

ix) Velocity Magnitude

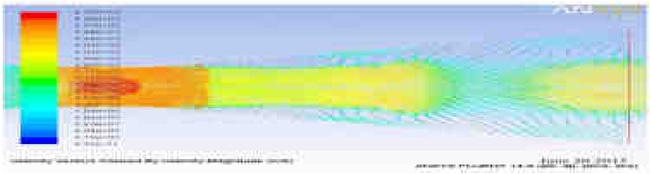

Fig. 1.18: velocity vectors contoured by velocity magnitude

x) Vorticity Magnitude

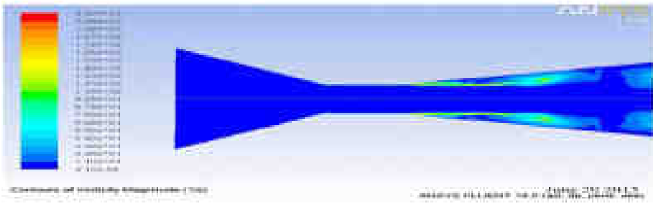

Fig. 1.19: contours of vorticity magnitude

b) Bell Nozzle results:

i) Density

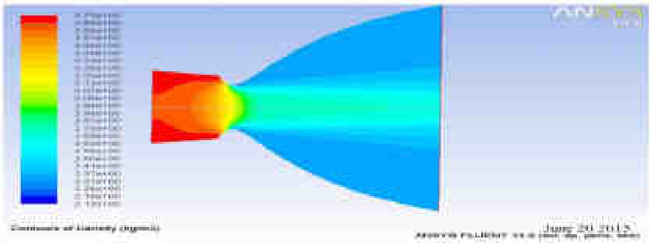

Fig. 1.20: contours of density

ii) Mach number

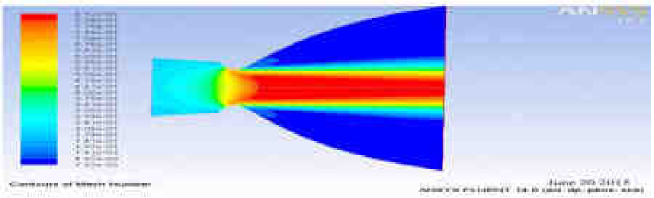

Fig. 1.21: contours of mach number

iii) Pressure

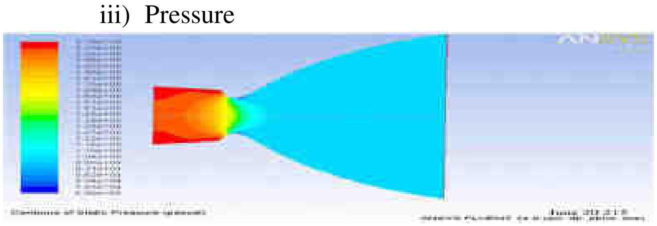

Fig. 1.22: contours of static pressure

iv) Velocity

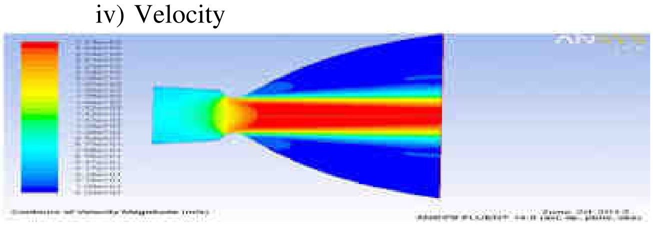

Fig. 1.23: contours of velocity magnitude

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v) Radial velocity

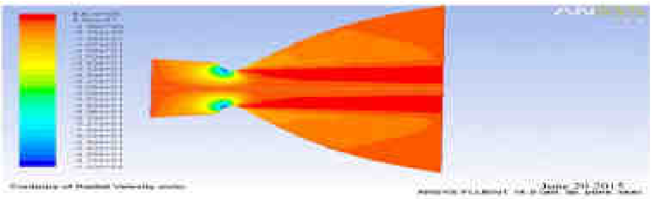

Fig. 1.24: contours of radial velocity

vi) Temperature

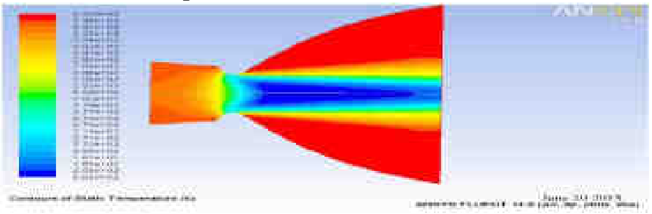

Fig. 1.25: contours of static temperature

c) Dual Bell Nozzle:

i) Pressure

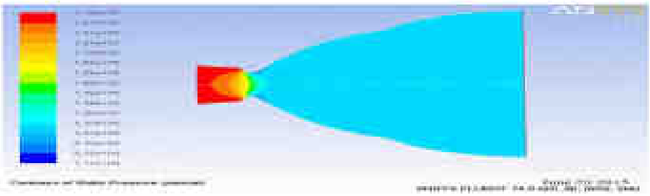

Fig. 1.26: contours of static pressure

ii) Density

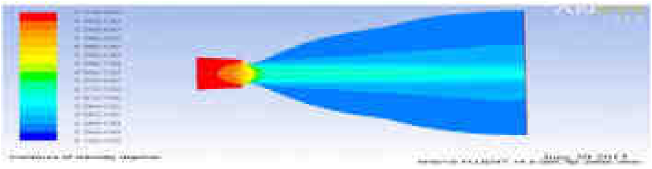

Fig. 1.27: contours of density

iii) Velocity

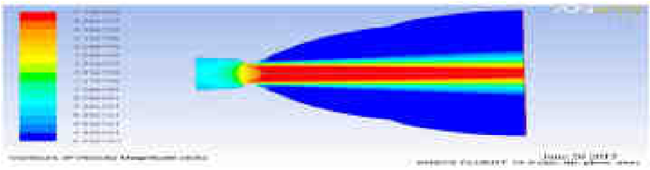

Fig. 1.28: contours of velocity magnitude

iv) Temperature

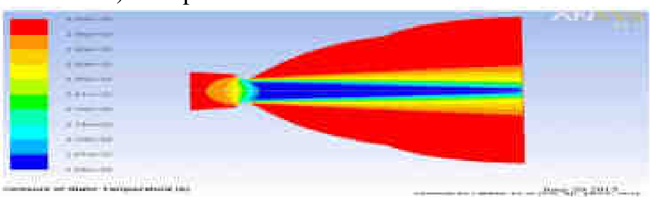

Fig. 1.29: contours of static temperature

v) Turbulence

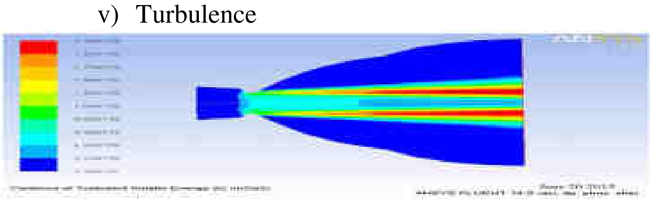

Fig. 1.30: contours of Turbulent Kinetic energy

d) Expandable Nozzle

i) Pressure

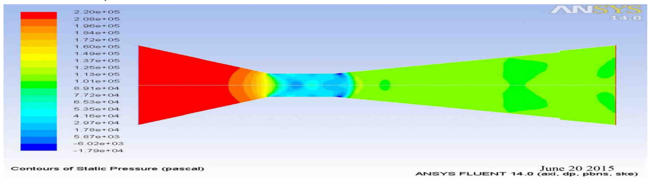

Fig. 1.31: contours of static pressure

ii) Density

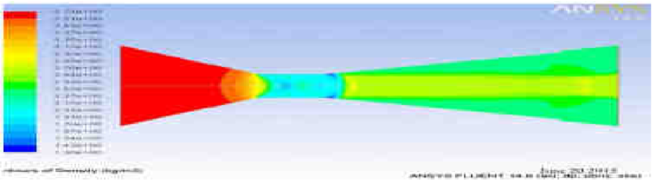

Fig. 1.32: contours of density

iii) Velocity Vectors

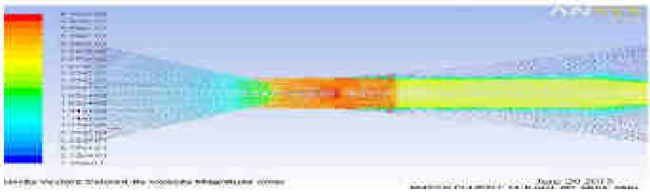

Fig. 1.33: velocity vector

iv)Temperature

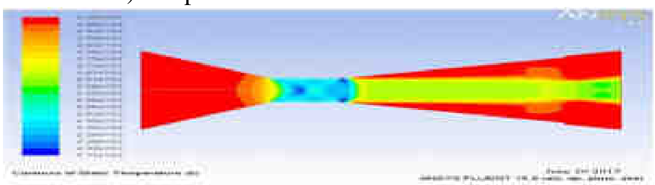

Fig. 1.34: contours of static temperature

v) Turbulent viscosity

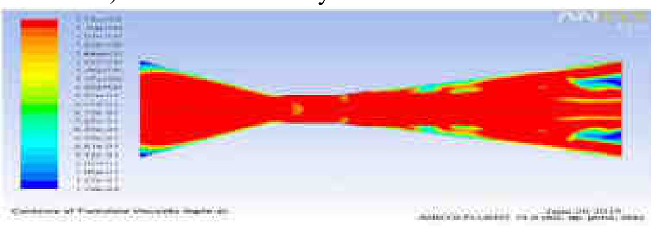

Fig. 1.35: contours of turbulent viscosity

vi) Turbulent Kinetic Energy

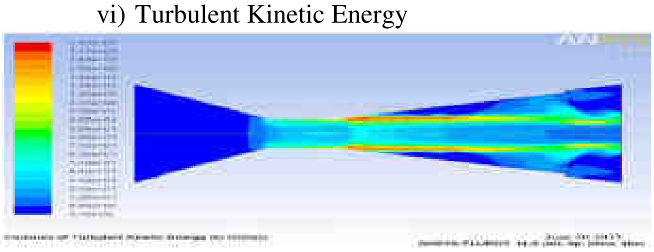

Fig. 1.36 contours of Turbulent Kinetic Energy

e) CD Nozzle experimentation with 32, 34, 40, 44 as External Diameters

External Diameter = 32

i) Pressure

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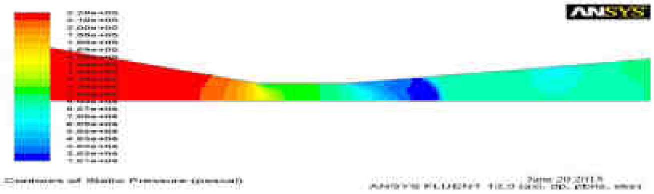
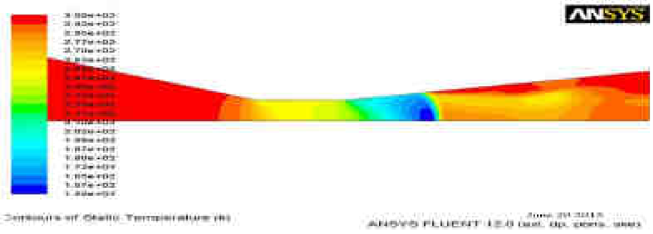
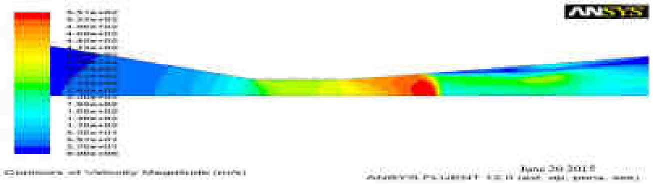


ii) Temperature

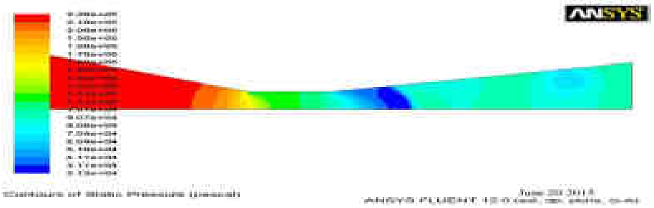


iii) Velocity

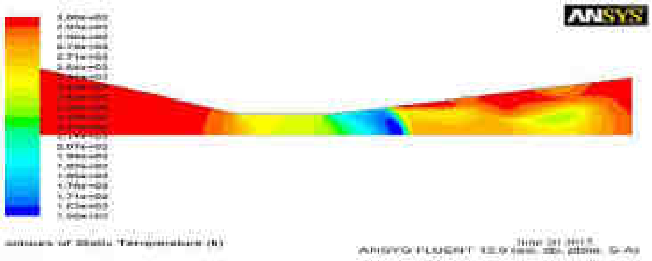


External Diameter = 34

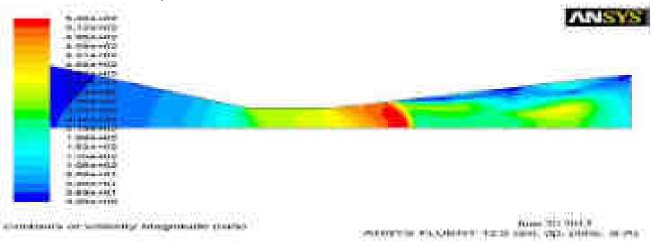
i) Pressure



ii) Temperature

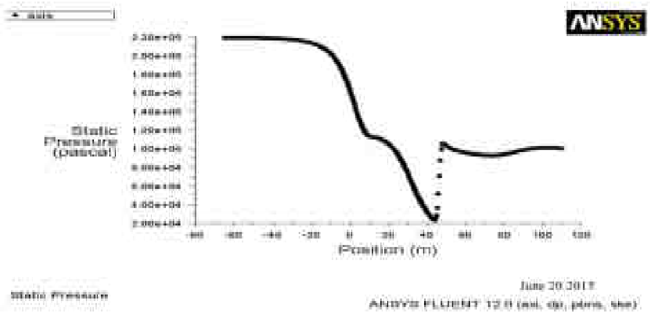


iii) Velocity

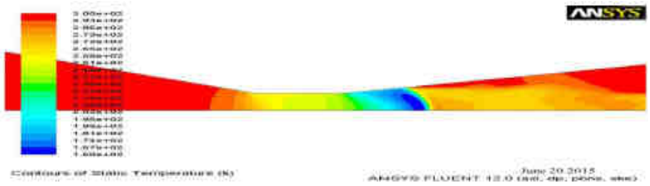


External Diameter = 40

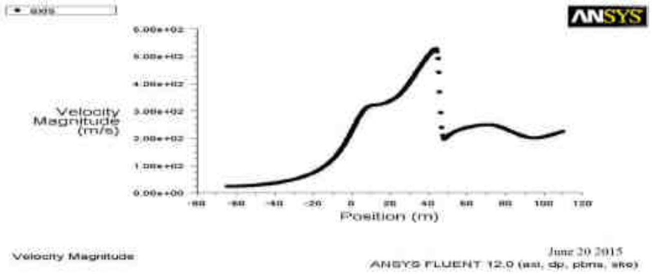
i) Pressure



ii) Temperature

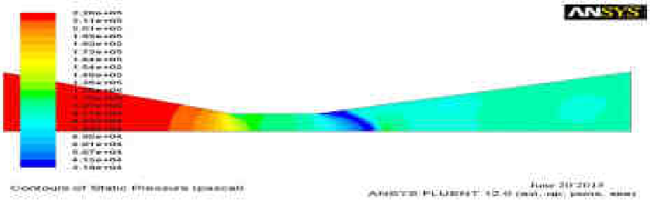


iii) Velocity

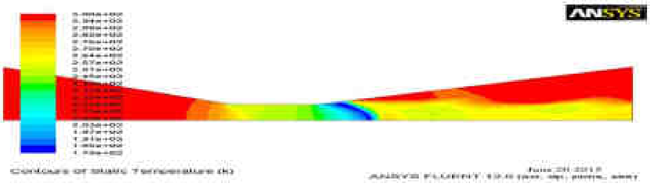


External Diameter = 44

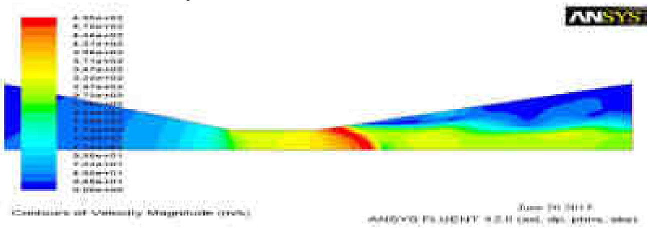
i) Pressure

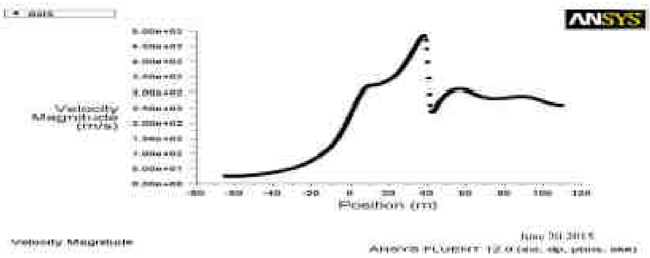


ii) Temperature



iv) Velocity





XII. RESULTS COMPARISION

Type of nozzle- Exit Velocity

Type of nozzle	Exit Velocity
CD Nozzle	4.29e+02
Bell Nozzle	2.73e+02
Dual Bell Nozzle	2.72e+02
Expandable Nozzle	4.00e+02

The order of exit velocity is;

CD nozzle > Expandable nozzle > Bell nozzle > Dual bell

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XIII. CONCLUSION

Because of greater value for exit velocity, we can conclude that convergent divergent nozzle can show better performance than bell nozzle, dual bell nozzle and expandable nozzles. Although benefits in performance were indicated in most of the available publications, not many of these nozzle concepts has yet been used in existing rocket launchers. It is shown that significant performance gains results from the adaptation of the exhaust flow to the ambient pressure. All of the advanced nozzle concepts have been to the subject of analytical work and gave much satisfactory results, but Convergent divergent nozzle stands as best among the nozzles we analyzed.

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