Design and analysis of contour bell nozzle and comparison with dual bell nozzle

Sreenath K R[1], Mubarak A K[2]
P G Scholar[1], Associate Professor[2], Govt.Engineering College Thrissur, Kerala

Abstract-
The performance and the thrust delivery of the engine such as nozzles are in renovation for the greater performance. Modern combustion expansion system like in rocket nozzles will be updated with respect to the application. Bell and Dual bell nozzle is the One of such development. Four different types of Bell nozzle one duel bell nozzle is selected and studied using computational fluid dynamics (CFD) in the present paper . The project mainly focuses on design and analysis of contoured convergent divergent bell nozzle. For the simulation, consider a 2D , parabolic contoured thrust optimized axisymmetric nozzle. The priority is given to design a bell nozzle with negligible shock wave. The temperature effects are not taken into this study, the flow is purely cold flow (303K). A full length Bell nozzle created using Gambit software. The meshing and analysis of the Bell model were done using FLUENT software. Air is taken as working medium for the nozzle and also for the ambience. Only one half of the nozzle is simulated due to symmetry reasons , and symmetry boundary conditions are used at the corresponding planes. The nozzle walls were set as adiabatic and assumed to be hydraulically smooth. A control volume was constructed around the nozzle to take the interaction with the ambience. The behavior of flow along the bell nozzle is thus obtained .

Keywords: *dual bell nozzle; convergent divergent nozzle; thrust optimized; shock wave; cold flow*

INTRODUCTION

A nozzle is a device designed to control the direction or characteristics of afluidflow as it exits an enclosed chamber orpipe. A pipe or tube of varying cross sectional area is generally considered as a nozzle, and it can be used to direct or modify the fluid flow. The velocity of fluid increases with pressure energy from inlet to outlet, in a nozzle. Nozzle flow always generates forces associated to the change in flow momentum. Flow analysis in nozzles is a subject of interest for researchers since it has vast applications in industries especially aircraft and rocket production industry because nozzle produces the required thrust. Large scale launch vehicle requires nozzle which can produce maximum thrust with reduced nozzle length.

Different types of CD nozzle geometries are, conical nozzles, bell nozzles, annular nozzles, spike nozzles, aero spike nozzle etc. Each nozzle geometry has its own structural considerations. In early rocket applications, conical nozzles were used because of ease of construction and simplicity. Most commonly used nozzle shape which offers significant advantages in size and performance over conical nozzle is Bell shape. Contour the nozzle to get maximize performance with negligible oblique shocks is the main issue which have to face here. Its shape is optimum only at one altitude. The design of Bell shape impart a large expansion angle right after the throat. It is then curved back to give a nearly straight flow of gas out the nozzle opening. The contour used is rather complex. An expansion shock wave is produced near the throat due to large expansion in shape. Compression shock waves generates due to reversal of slope to bring the exit to near zero degrees causes. These two sets of shock waves coincide and cancel each other out, in a properly designed bell nozzle.

Optimum performance of the nozzle obtained when the exit pressure equals ambient (atmospheric) pressure. For the rocket travelling from Earth to orbit pressure varied with altitude. Therefore a simple nozzle design is only optimal at one altitude, losing efficiency and wasting fuel at other altitude.

BELL AND DUAL BELL NOZZLE

Bell Nozzle gets its name from the fact that the parabolic shape converge and diverge in a bell shape. It has a high angle expansion section right behind the nozzle throat; this is followed by a gradual reversal of nozzle contour slope so that the nozzle exit divergence angle is small, usually less than a 10 degree half angle. Greater thrust produced due to the parabolic shape maximizes the axial component of exit velocity and produces a high specific impulse.Contour the nozzle to avoid oblique shocks and maximize performance is the most important design issue.

The nozzle works over expanded at sea level and strongly under expanded at altitude. Various concepts of altitude adaptive nozzles have been proposed in the literature to circumvent this limitation. The dual bell nozzle is a very promising alternative to conventional nozzles. The dual bell is a nozzle concept for altitude adaption. The flow separates at the contour inflection in sea level mode in a mainly controlled and symmetrical way, reducing the side load generation and increasing the thrust. The transition to altitude mode is reached when the flow suddenly attaches to the extension for an improved altitude thrust.

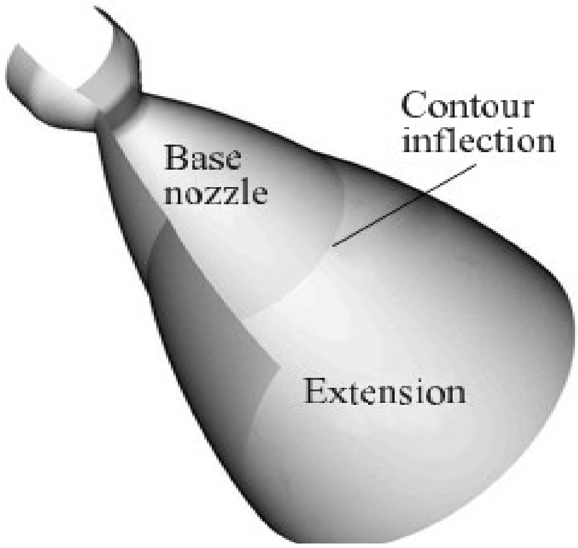


Fig.1 dual bell nozzle

LITERATURE SUMMARY

Nozzle is an area where a lot of research work is being carried out. This chapter presents a few works published by various researchers in the field of supersonic flow analysis , design of bell nozzle and the inference obtained from those works.

Rao,developed a method for designing the wall contour of an exhaust nozzle to yield optimum thrust. K.M. Pandey , conducted studies to understand the gas flows in a conical nozzle at different degree of angle using 2 dimensional axi-symmetric models. Munday et al, conducted experiments and numerical simulation on conical convergent divergent nozzles with a design Mach number of 1.56. David Munday and Ephraim Gutmark, conducted an experimental and numerical

PARAMETER	NOZZLE 1	NOZZLE 2	NOZZLE 3	NOZZLE4
Throat RaidusR$_{th}$(mm)	8	8	6	6
Exit area, a$_e$(mm^2)	236.3625	236.3625	146.0724	132.9539
Exit area ratio, a_e/a_t	1.10698	1.10698	1.29222	1.1762
Inlet area ratio, a_i/a_t	1.29222	1.29222	1.778	1.778
specific heat ratio, γ	1.4	1.4	1.4	1.4
Nozzle exit mach number, m$_e$	1.5	1.5	1.65	1.5
Nozzle exit pressure p$_e$(pasc)	101325	101325	101325	101325

analysis on supersonic jets to study the flow structure of jets. Verma et al , carried out a study of the unsteady nature of flow phenomenon in thrust optimized parabolic rocket nozzles as a function of phase during which the separation shock jumps downstream at a certain nozzle pressure ratio. BalajiKrushna.P, P. SrinivasaRao, B. Balakrishna, conducted a numerical analysis of dual bell rocket nozzle using computational fluid dynamics. Linwood B. Callis , of Langley Research Centre used the method of axisymmetric irrotational characteristics in the analysis of supersonic and hypersonic flow of a calorically perfect gas through conical nozzles.

METHODOLOGY

After a detailed study of theoretical approach to the nozzles, a full length Bell nozzle is created using Gambit software. The meshing also done by using Gambit, and for the analysis of this Bell model, FLUENT software is used. Flow behavior along the bell nozzle is thus obtained and comparison on the basis of Mach number for various nozzles is henceforth done.

Air is taken as working medium for the nozzle and also for the ambience. The initialization of value is computed from the inlet. Here we have to select the appropriate approximation required in the residual command under monitors and check in plot to visualize the iteration progress. Once every parameter is described the iteration is performed till the value gets converged to required approximation. The Figures can be plotted between position in x-axis and any other function in y-axis from plot command or else to view vectors, contours or grid display command is to be chosen. A mathematical model consists of differential equations that govern the behavior of the physical system, and the associated boundary conditions.

BELL DESIGN

A TOP nozzle is constructed using three curves : an initial, large circle coming from the inlet to the throat, a smaller circle exiting the throat, and a parabola to extend the approximated bell contour to the exit plane. The length of the nozzle is determined by

$$L_n = \frac{K\left(\sqrt{\varepsilon}-1\right)R_t}{\tan(\theta_e)}$$

where K is a value chosen based on the percent of the length of a conical nozzle with a 15° half angle, the flow deflection angle at the exit, Ѳe , and the throat radius, R$_t$. In order to define the nozzle further, a coordinate system is defined with the axial (x) axis passing through the line of symmetry and the radial (y) axis going through the Centre of the throat. The first and second curves define the entrance and exit of the throat of the nozzle, and are based on circular curves.

$$x^2 + (y - (R_t + 1.5R_t))^2 = (1.5R_t)^2$$

$$x^2 + (y - (R_t + 0.382R_t))^2 = (0.382R_t)^2$$

The equation of the parabola, curve 3, takes the form

$$x = ay^2 + by + c$$

The coefficients are determined by the derivatives at the point where the circle from the throat meets the beginning of the parabola, x$_N$, and the length of the nozzle. To determine x$_N$, the angle, Ѳ$_N$ needs to be defined, then the derivative of the second curve should be equal to its tangent.

$$\frac{dy}{dx} = \tan(\theta_N) = \frac{x_N}{\sqrt{(0.382R_t)^2 - x^2}}$$

$$x_N = aR_N^2 + bR_n + c$$

$$\frac{dy}{dx} = \tan(\theta_N) = \frac{1}{2aR_N + b}$$

$$\frac{dy}{dx} = \tan(\theta_e) = \frac{1}{2aR_e + b}$$

This completes the linear system of equations. In matrix form, the system is .

$$\begin{bmatrix} 2R_N & 1 & 0 \\ 2R_e & 1 & 0 \\ R_N^2 & R_N & 1 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} \frac{1}{\tan(\theta_N)} \\ \frac{1}{\tan(\theta_e)} \\ x_N \end{bmatrix}$$

which can then be solved for the coefficients.

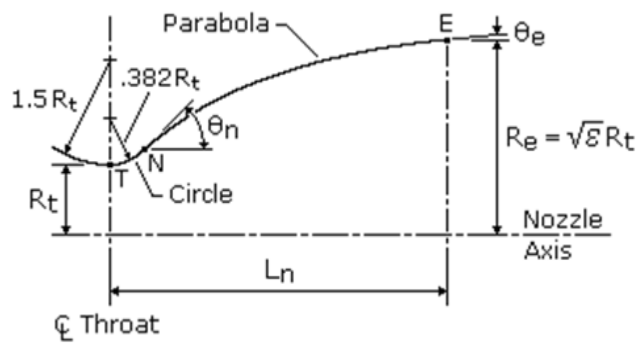


Fig.2 Rao design of Bell nozzle contour

FLOW ANALYSIS

Flow analysis for the bell nozzle is carried out using ANSYS 15.0 Fluent software. In this process first the models are meshed, imported and flow analysis is carried out in major three steps

- GAMBIT, where the meshed model is drawn and boundaries are created and corresponding boundary conditions are assigned to the boundaries.

- FLUENT-SOLVER, where the solutions are obtained by solving the equations and process is highlighted in terms of codes and graphs and once the run is over it reaches next step.
- FLUENT, where the corresponding contours are created for following major parameters such a Pressure, Temperature and Mach number.

DESIGN PARAMETERS

RESULTS AND DISCUSSION

1.BELL NOZZLE 1

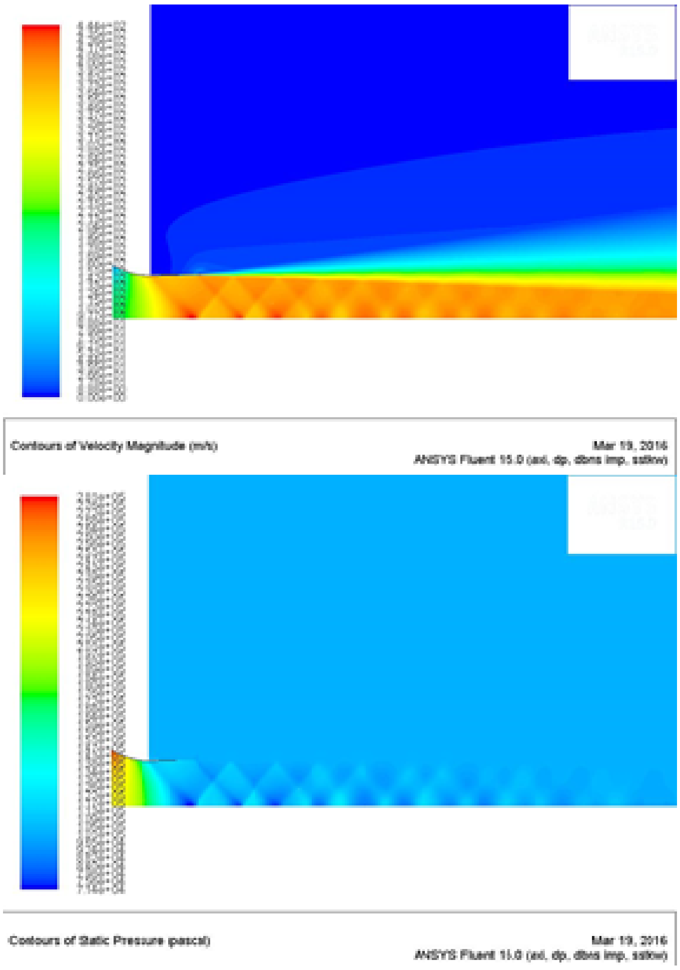


Fig.3 Contours of Velocity Magnitude & Static Pressure for nozzle 1

Magnitude of the velocity is found to increase as move from inlet to exit .At the inlet the max velocity is found to be 205.75 m/s .The magnitude of velocity varies from 0 to 443.922 m/s . The velocity at the throat varies from 315.52 m/s to 358.38 m/s . At the exit the velocity is found to be 443.922 m/s (super-sonic). The static pressure at the inlet is observed to varies from 218111.6 Pa to 280678.3 Pa and as move towards the throat there is a decrease and the value at the throat is found out to be 168513.9 Pa. After some distance from the throat, there is a sudden increase in the static pressure near the axis which indicates the occurrence of the shock. After the shock there is a slight decrease in the pressure but it again rises at the second shock. Then it reduces to a value of 106700.2 Pa at the exit section due to the expansion of the fluid towards the exit of the nozzle .The value of static pressure varies in the range 71437.17 Pa to 280678.3 Pa .

2. BELL NOZZLE 2

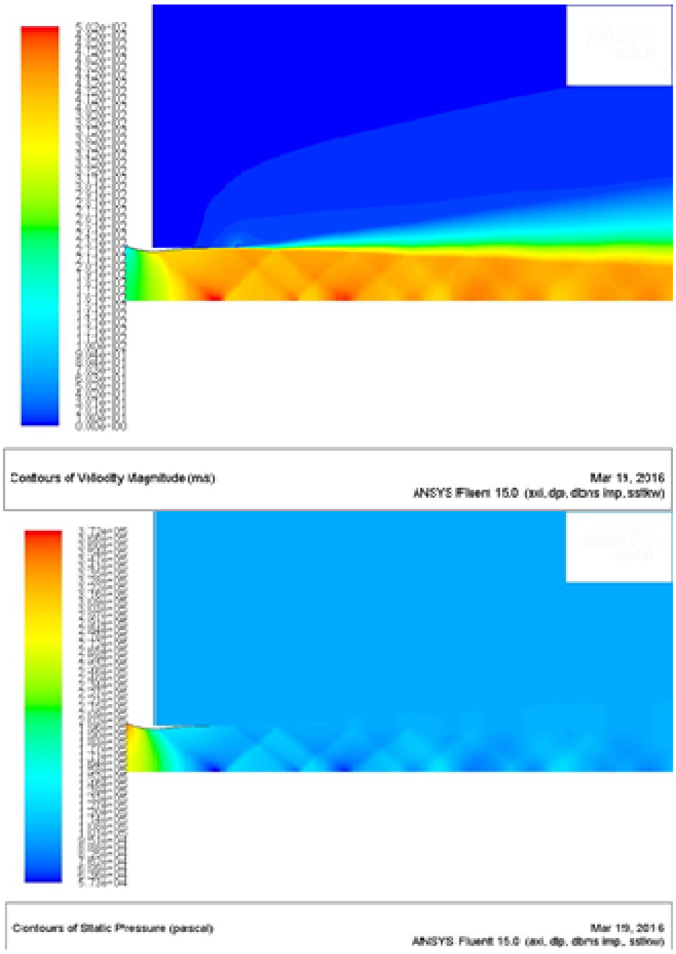
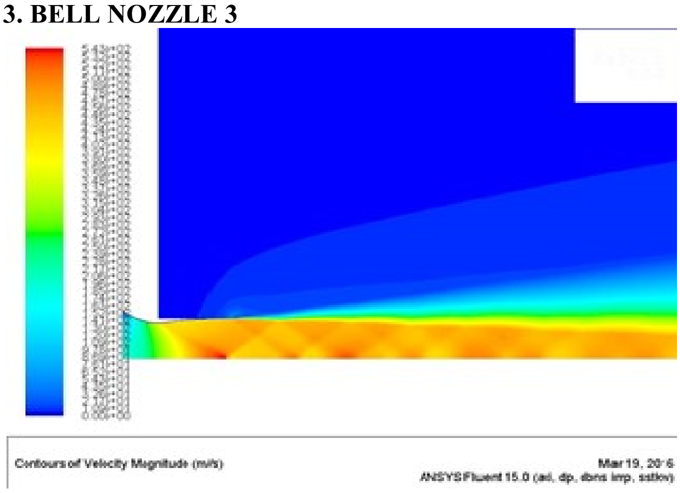


Fig.4 Contours of Velocity Magnitude & Static Pressure for nozzle 2

At the inlet the max velocity is found to be 235 m/s .The magnitude of velocity varies from 0 to 502.3456 m/s . The velocity varies at the throat from 317.32 m/s to 357.32 m/s .At the exit the velocity is found to be 440.67 m/s (super-sonic). Magnitude of the velocity is found to increase as move from inlet to exit The static pressure at the inlet is observed to vary from 266854.7 Pa to 372497.8 Pa and as move towards the throat there is a decrease and the value at the throat is found out to be 221461.3 Pa. The value of static pressure varies in the range 57271.64 Pa to 372497.8 Pa .

3. BELL NOZZLE 3



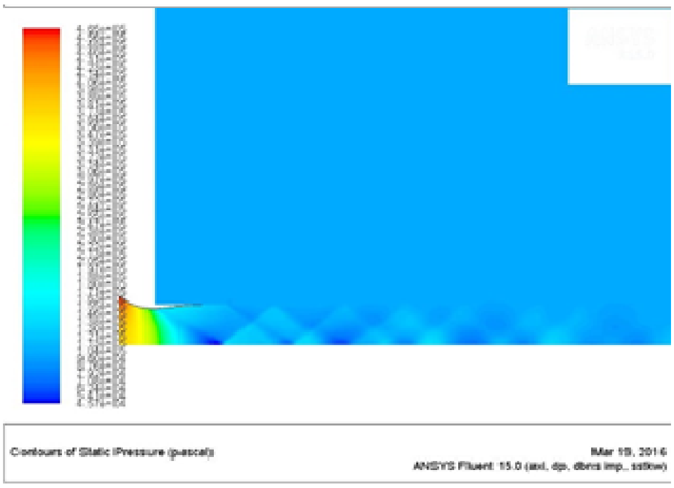
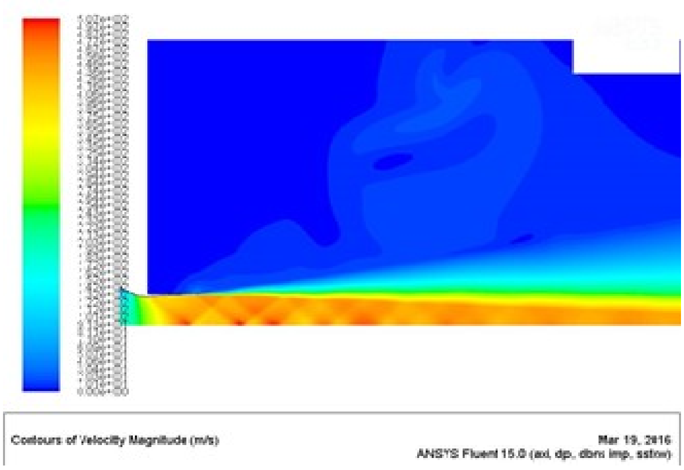


Fig.5 Contours of Velocity Magnitude & Static Pressure for nozzle 3

At the inlet the max velocity is found to be 190.1 m/s .The magnitude of velocity varies from 0 to 543.34 m/s . The velocity varies from 320.4 m/s to 360.5 m/s, at the throat section . The velocity at the exit is found to be 475.17 m/s (super-sonic). The static pressure vary from 375271.4 Pa to 464793.6 Pa at the inlet and as move towards the throat there is a decrease and the value at the throat is found out to be 279982.5 Pa. The value of static pressure varies in the range 45676.64 Pa to 464793.6 Pa .

4. BELL NOZZLE 4

The magnitude of velocity is found to increase as move from inlet to exit .Max velocity at the inlet is found to be 190.1 m/s .The velocity magnitude varies from 0 to 507.118 m/s . At the throat section the velocity varies from 319.4 m/s to 361.5 m/s . The velocity at the exit is found to be 442.97 m/s (super-sonic). At the inlet static pressure is observed to vary from 309657.8 Pa to 383518.4 Pa .The value of static pressure varies in the range 56242.85 Pa to 383518.4 Pa .



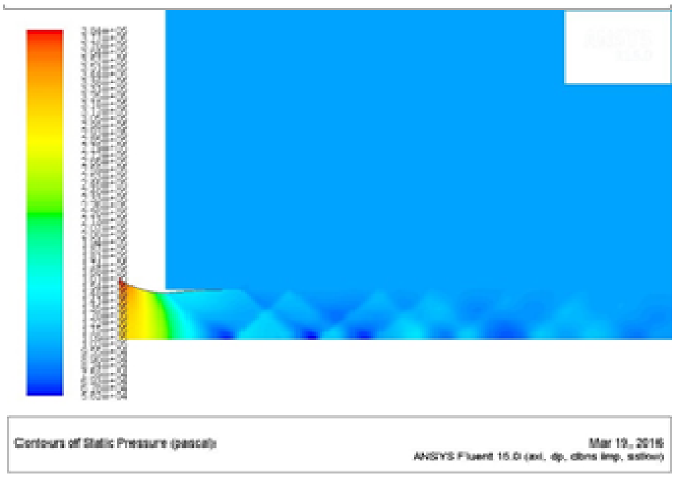


Fig.6 Contours of Velocity Magnitude & Static Pressure for nozzle 4

5. DUAL BELL NOZZLE

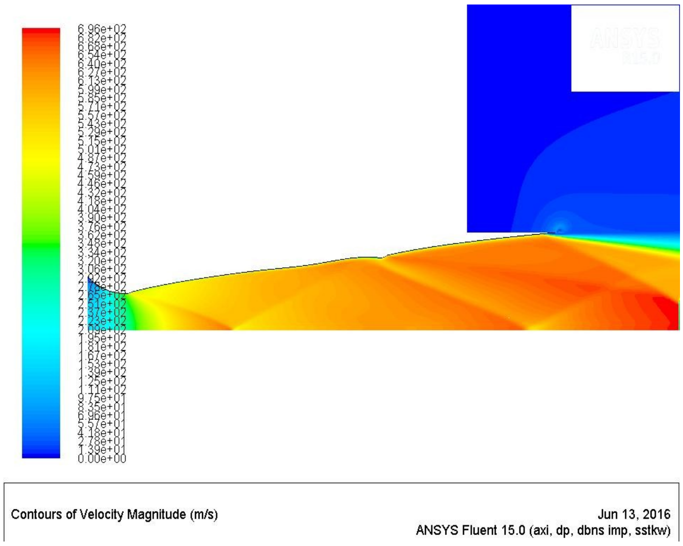


Fig.7 Contours of Velocity Magnitude for dual bell nozzle

Comparing the contour obtained for dual bell with the above single bells, there is an additional shock wave is seems to be obtained from the end point of first bell .This increase in number of shock waves cause to the chance of coincidence for the shock waves . The interference of two or more shock waves will reduce the strength of that waves and will give more advantage to the nozzle for flow .Here the additional shock wave has a chance to interfere with the wave produced from the throat and hence the combination will reduce the strength of both waves .At the high altitude mode or in under expanded condition , due to high pressure difference , the flow will be more attached to the nozzle wall at the second bell or external curve which will reduce the chance for a flow separation .

CONCLUTION

The dual bell nozzle has better overall performance than the single bell-shaped nozzle. Atmospheric pressure restricts the expansion of the exhaust gas at low altitudes so the efficiency is much higher at low altitudes . At low altitudes, a vehicle can saves 25-30% more fuel by using a dual bell nozzle. It is also able to expand the engine exhaust to a larger effective nozzle area ratio, at high altitudes. The dual bell design is suitable for Single Stage to Orbit (SSTO) flight. Better use of the base area, and has higher thrust efficiency and thus a higher average specific impulse are the other advantages of dual bell nozzle .

The numerical results are in good agreement at sea-level mode. The numerical method yields a good simulation from the flow behavior and helps to improve the understanding of the physics of the flow. Simulation of four supersonic flow bell nozzles with different Mach number at exit was done here .On analyzing the different contours of the flow behavior , we can get a clear cut shock structure in each bell nozzle design .Out of the above four bell nozzle numerical simulation comparisons, the bell nozzle with 1.5 Mach number at the exit gives less shock and better flow separation behavior .

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