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DESIGN OF EXPANSION DEFLECTION NOZZLE

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Abstract
In the field of rocket propulsion, design of nozzle is of paramount importance. Development of the nozzle with the capability of producing optimum amounts of thrust in wide ranges of altitude has been a subject of continuous dedicated efforts within the community of rocket propulsion. The phenomenon of producing optimum amounts of thrust by a rocket nozzle in off-design conditions is called as altitude compensation. Nozzles with the altitude compensation characteristics are basic feature in realizing the development of Single Stage to Orbit (SSTO) vehicles. Reusable SSTO vehicles offer the promise of reduced launch expenses by eliminating recurring costs associated with hardware replacement inherent in expendable launch systems.

***Key Words**: Design, Nozzle, Deflection.*

INTRODUCTION

In the field of rocket propulsion, design of nozzle is of paramount importance. There are many types of nozzles, for example conical nozzle, 80% nozzle, convergent divergent nozzle, bell nozzle, etc., used according to the requirements of the mission. Development of the nozzle with the capability of producing optimum amounts of thrust in wide ranges of altitude has been a subject of continuous dedicated efforts within the community of rocket propulsion. The phenomenon of producing optimum amounts of thrust by a rocket nozzle in off-design conditions is called as altitude compensation. Nozzles with the altitude compensation characteristics are basic feature in realizing the development of Single Stage to Orbit (SSTO) vehicles. Reusable SSTO vehicles offer the promise of reduced launch expenses by eliminating recurring costs associated with hardware replacement inherent in expendable launch systems. The most popular altitude compensating rocket nozzle to date is the Expansion deflection nozzle, the origin of which dates back to Rocket dyne in 1950s. An altitude compensating nozzle is a class of rocket engine nozzles that are designed to operate efficiently across a wide range of altitudes. Types of altitude compensating nozzles can be listed as follows

- Plug nozzle/ Spike nozzle
- Expanding nozzle
- Single expansion ramp nozzle
- Stepped nozzle
- Expansion deflection (ED) nozzle
- Nozzle extension

Besides the use of above type of nozzles methods like multistage and tri-propellant rockets are used for altitude compensation.

Expansion deflection nozzle

The expansion-deflection nozzle is an advanced rocket nozzle which achieves altitude compensation through interaction of the exhaust gas with the atmosphere, much like the plug and aerospike nozzles. It appears much like a standard bell nozzle, but at the throat is a 'centre body' or 'pintle' which deflects the flow towards the walls. The exhaust gas flows past this in a more outward direction than in standard bell nozzles while expanding before being turned towards the exit. This allows for shorter nozzles than the standard design whilst maintaining nozzle expansion ratios. Because of the atmospheric boundary, the atmospheric pressure affects the exit area ratio so that atmospheric compensation can be obtained up to the geometric maximum allowed by the specific nozzle. The nozzle operates in two distinct modes: open and closed. In closed wake mode, the exhaust gas fills the entire nozzle exit area. The ambient pressure at which the wake changes from open to closed modes is called the design pressure. If the ambient pressure reduces any further, additional expansion will occur outside the nozzle much like a standard bell nozzle and no altitude compensation effect will be gained. In open wake mode, the exit area is dependent on the ambient pressure and the exhaust gas exits the nozzle as an annulus as it does not fill the entire nozzle. Because the ambient pressure controls the exit area, the area ratio should be perfectly compensating to the altitude up to the design pressure.

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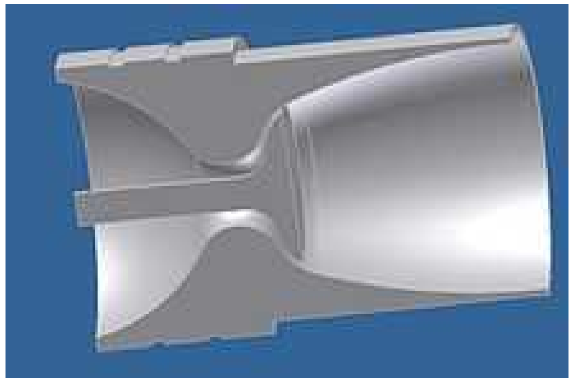

Figure.1.1: An Expansion deflection nozzle clearly shows the pintle

If the pintle is designed to move along its axis of rotation, the throat area can be varied. This would allow for effective throttling, whilst maintaining chamber pressure. Like the aerospike and plug nozzles, if modular combustion chambers were used in place of a single combustion chamber, then thrust vectoring would be achievable by throttling the flow to various chambers. Traditional converging-diverging nozzles have a single ambient pressure at which the rocket exhaust gases are neither over-expanded nor under-expanded. As the operating conditions move away from the design nozzle pressure ratio (NPR), a shock or an expansion fan will form at the exit plane of the converging-diverging nozzle.

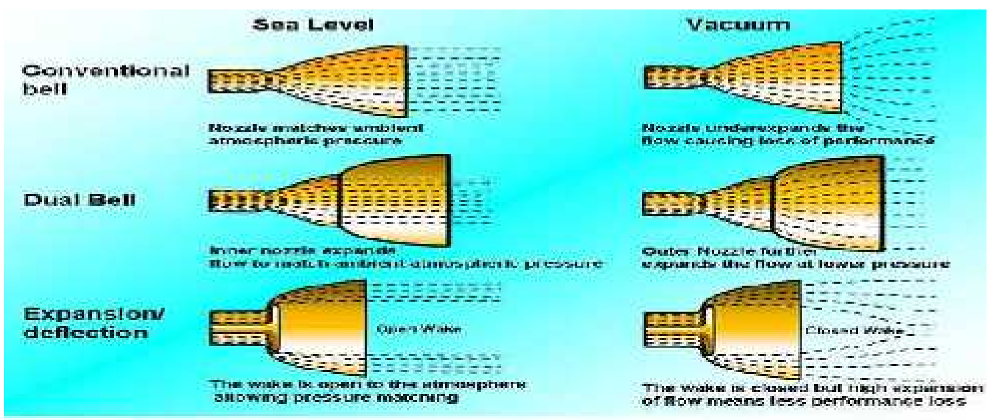

Figure.1.2: Expansion-deflection nozzle behaviour in comparison with traditional Nozzles during flight

These result in reductions in the efficiency of the nozzle. An Expansion-deflection nozzle does not have a solid geometry defining the outer limits of the flow path in the supersonic region of the flow. Instead it allows the exhaust gases to expand freely beyond the throat, via the mechanism of a Prandtl-Meyer expansion fan.

OBJECTIVES OF THE STUDY

The present work has been done in focus with the development of a nozzle for the Single Stage to Orbit vehicle with the following objectives.

1. Design of Expansion deflection nozzles in the 4-5 KN thrust class with varying amounts of truncation.
2. Comparing results with a conventional bell nozzle and modifying the Expansion deflection nozzle to study the performance characteristics.

SCOPE OF THE STUDY

1. Design of linear Expansion deflection nozzle with lengths of 25% - 30%.
2. Validation of the design is done by numerical simulation using commercial Computational Fluid Dynamics (CFD) code ANSYS FLUENT.

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3. The nozzle flow-field is obtained and studied using ANSYS FLUEN

REVIEW OF LITERATURE

Many theoretical studies of the Expansion deflection nozzle have been carried out in 1960s. Berman and Crimp's work is an example of these studies, in which issues such as analytical design methods, thrust vectoring, and integration with solid- and liquid-propellant systems have been addressed. G. V. R. Rao has presented a more accurate method based on calculus of variations for design of the pintle in 1961. Lee and Thompson are the first to develop the computer program for plug nozzle design. The programs described in their report "FORTRAN programs for plug and expanded nozzle design" are simple and provide a scheme for the design of a plug and expanded nozzle contour. However, this method becomes inaccurate as the axis of symmetry is approached. Two FORTRAN computer programs for the design of pure external and internal-external expansion expanded nozzles are described in this report. The output from these programs includes the contour of the nozzle and various performance parameters. The approximate design method is based on simple wave flow concepts which are described by T. L. Deyound. The ratio of specific heats in this program may be input either as a constant value or as a function of Mach number. The thrust coefficient, specific impulse, and dimensionless contour co-ordinates are computed at small increments along the axis of symmetry. In the study "NUMERICAL INVESTIGATION OF FLOW PHENOMENA IN A PLANAR EXPANSION-DEFLECTION NOZZLE" by Gerrit-Daniel Stich, Bernd Wagner, and Stefan Schlechtriem, A generic planar expansion-deflection nozzle in linear configuration has been investigated with the CFD tool TAU, which is developed by the German Research Center - DLR. It is part of a parallel conducted cold gas test campaign. Following the philosophy of decomposing problems to singular sub problems, an intensive validation study has been performed in addition and compared to data taken from literature. Different turbulence models, grid density, and mesh adaption have been assessed for the test cases as well as for the expansion-deflection nozzle. Especially, the Spalart-Allmaras turbulence model shows overall satisfying results and has a benefit in performance and robustness. Based on that experience, the nozzle flow was simulated in a pressure ratio range from 2 - 30, for both increasing and decreasing pressure gradient on 2d and 3d domains. The results are discussed concerning flow transition, hysteresis effect, three dimensional wake flow, and flow separation at the side wall. A group of researchers Mehdi Nazarinia, ArashNaghib-Lahouti and ElhaumTolouei from Aerospace Research Institute, Iran, studied the exhaust flow features and performance characteristics of the conical aerospike nozzle in 4-5 KN thrust class and they also studied the effect of base-bleed on the over-all performance of the nozzle. They observed that the nozzle performance is not influenced by truncation as the base pressure compensates the loss of thrust force, whereas truncation will increase the thrust loss in overexpansion condition. Therefore lower values of truncation are chosen if most of the thrusters flight phase is going to be at over-expansion conditions that are at altitudes lower than the design altitudes. Aerospike nozzles can deliver 5% more thrust in over-expansion condition, which is required for the launch vehicles. They also studied the thermal distribution at the base of the plug and stated that adding curvature to the base of truncated plug improves local temperature distribution. It is also mentioned that the parts of the expansion waves encounter the rotational base flow.

METHODOLOGY

A 2-D design is developed based on the design method used for an Expansion deflection nozzle. Design of the Expansion deflection nozzle mainly refers to the design of the central pintle and the determination of angle of the primary nozzle. Design of the central contour of the nozzle can be done by two methods namely the method of characteristics, approximation Method.

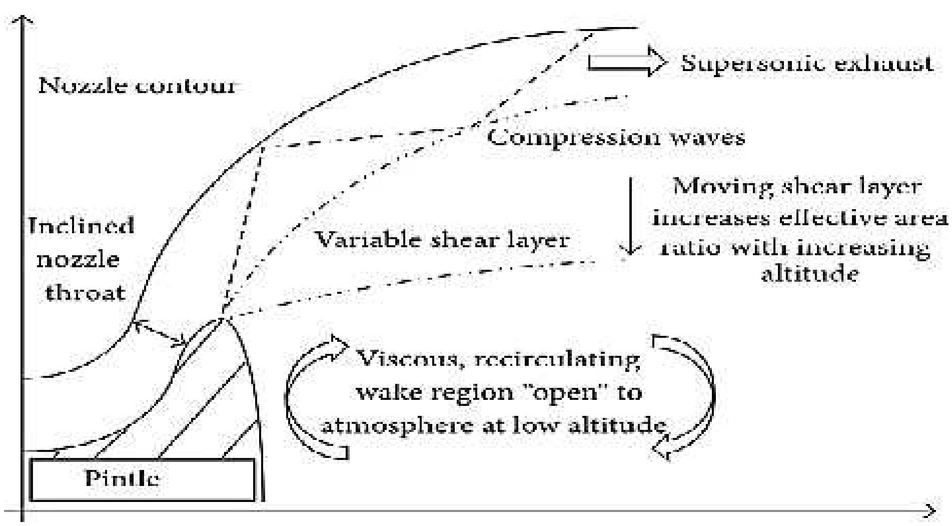

Figure 1.3: Half diametric cross section of the expansion-deflection nozzle behaviour in open mode.

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Greer, 1960, describes a method which uses geometry and the isentropic area ratio equation to define the contour of the expansion-deflection nozzles. First, before we discuss the method, it is important to note that the angle the direction of the flow at the throat makes with the nozzle's axisymmetric line at the beginning of the external expansion is equal to the Prandtl-Meyer expansion angle for the user-defined desired exit Mach number. Using this angle as the sonic flow direction, the Prandtl-Meyer expansion fan cantered at the tip of the cowl located at the end of the sonic line furthest from the nozzle's axisymmetric line can be stepped through by a user-defined Prandtl-Meyer expansion angle increment. For each Prandtl-Meyer expansion angle stepped through, its associated Mach number can be calculated. Using the Mach number and geometry, the length of the line from the tip of the cowl is known from the isentropic area ratio equation. From geometric manipulation and the flow properties of an expansion fan, the slope of the line emanating from the tip of the cowl can be calculated. Since the tip of the cowl can be geometrically set by the designer, the points located on the nozzle's contour can be calculated using trigonometry. Greer non-dimensionalized the calculation by dividing the length of the lines emanating from the tip by the length associated with the desired exit Mach number. The calculations are stepped through until the desired exit Mach number is obtained. It is also important to note that the flow properties along the lines emanating from the tip of the cowl are assumed to be constant. This is important because the curved nature of the characteristics is not taken into account for the calculation of axisymmetric nozzles introducing errors. The points on the contour are then connected by line segments to make the aerospike's contour. This method is accurate when comparing the exit to throat area ratio since the isentropic area ratio is used in defining the contour. The contour becomes smoother as the number of points defining the contour increase, aka the Prandtl- Meyer expansion angle increment decreases.

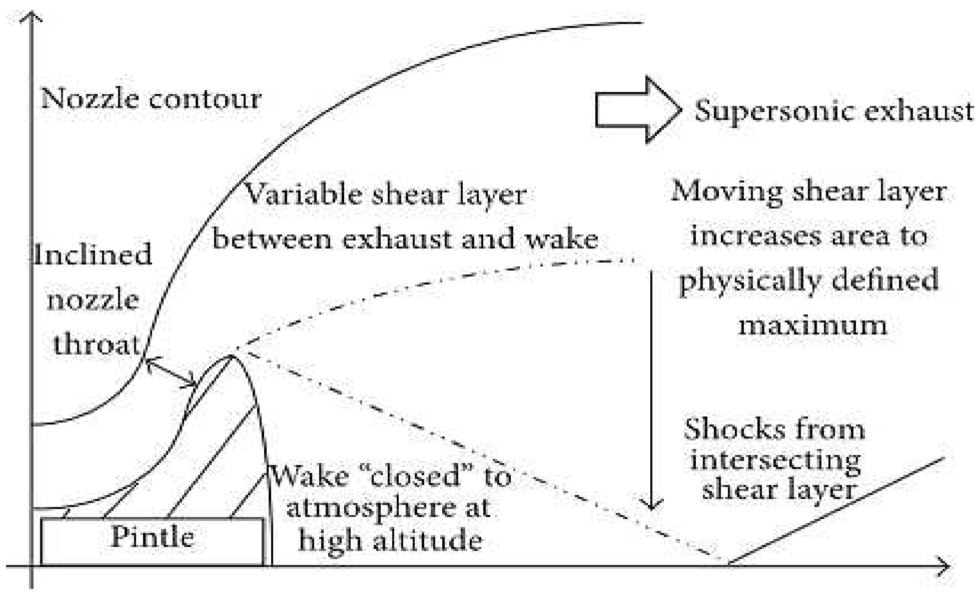

Figure 1.4 : Half diametric cross section of the expansion-deflection nozzle behaviour in closed mode.

APPROXIMATION METHOD

Another approximate method for defining a traditional Expansion deflection nozzle is outlined by Angelino, 1964. He used a method similar to Greer only instead of using geometry to define the angle the characteristic made with the axisym metric line, he used the characteristic equations. For an expansion fan, the angle the Mach line (characteristic) makes with the geometric x-axis is known through the equation $\varphi = \alpha (M) + \theta$ Like the method described by Greer, the direction the flow at the throat makes with the x-axis is equal to the Prandtl- Meyer expansion angle, and the calculation sweeps through the expansion fan by a user defined Prandtl-Meyer expansion angle increment. For each step, the Mach number associated with each Prandtl-Meyer expansion angle is calculated. After the Mach number is known, the length of the characteristic line can be calculated using the isentropic area ratio equation and geometry for the given Mach number. Since the flow direction at the throat is known, the flow direction at each calculation step is known because for every incremental increase in the Prandtl-Meyer expansion angle in an expansion fan, the angle the direction of the flow makes with the x-axis decreases the same incremental amount. Since the location of the tip of the cowl is a user-defined quantity, the location of each point on the Expansion deflection's contour can be calculated using trigonometry for each characteristic. This is continued until the user-defined exit Mach number is reached. To non-dimensionalize the equations, Angelino also divided the equation for the length of the characteristic by the isentropic area ratio associated with the desired exit Mach number. As with the method described

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by Greer, Angelino's method is also accurate with respect to the isentropic area ratio for the desired exit Mach number since this relation is used in the derivation of the lengths of the characteristics. It is important to note that although the exit area of the Expansion deflection nozzles described by Greer and Angelino are the same and equal to the idealized isentropic area ratio, the contours calculated by the methods will be slightly different from one another. Among the various approximation methods Angelino's approximation method based on ideal rocket assumptions is used in many cases for the design of the central pintle, because of its simplicity and the accuracy of the calculations. By using approximation method exhaust and throat area of the aerospike nozzle is calculated as

Area of exhaust $A_e = \pi(\mathrm{r}_e^2 \quad \mathrm{r}_b^2)$ *Eq. 1.1*

Area of throat $A_t = \frac{\pi(\mathrm{r}_e^2 - \mathrm{r}_t^2)}{\cos\theta_t}$ *Eq. 1.2*

In an isentropic supersonic flow, an area ratio can be written as follows

$$\frac{A_e}{A_t} = \epsilon = \frac{1}{M_e}\left[\left(\frac{2}{\gamma+1}\right)\left(1 + \frac{\gamma-1}{2}{M_e}^2\right)\right]^{\frac{\gamma+1}{2(\gamma-1)}}$$ *Eq. 1.3*

The above equation gives the relationship between the Mach number and area ratio. From the following Prandtl-Meyer relation, a total flow turning angle can be calculated,

$$\upsilon = \left(\frac{\gamma+1}{\gamma-1}\right)^{\frac{1}{2}} tan^{-1}\left[\frac{\gamma-1}{\gamma+1}(M^2-1)\right]^{\frac{1}{2}} - tan^{-1}(M^2-1)^{\frac{1}{2}}$$ *Eq. 1.4*

Throat angle is given by $\theta t = (Me)$ *Eq. 1.5*

METHOD OF CHARACTERISTICS

Another method used for calculating the contour of a Traditional Expansion deflection contour is described by Lee and Thompson, 1964. Their method uses the Method of Characteristics in conjunction with the Stream Function to define the contour. This method is similar to the technique employed by Shapiro. As with the methods outlined by Greer and Angelino, the flow direction at the throat is set at an angle equal to the Prandtl- Meyer expansion angle associated with the user-defined exit Mach number. The Prandtl- Meyer expansion fan is centred at the tip of the cowl and its location is user-defined. Unlike the other two methods described above, this method calculates the end point of the aerospike's contour first and sweeps through the Prandtl-Meyer expansion fan backwards, starting with a flow direction equal to zero and the Prandtl-Meyer expansion angle equal to the Prandtl-Meyer expansion angle associated with the desired exit Mach number. The flow direction is increase while the Prandtl-Meyer expansion angle is decreased by a user-defined Prandtl-Meyer expansion angle increment. The last contour point is calculated using the isentropic area ratio for the desired exit Mach number in conjunction with the angle the characteristic makes with the x-axis given by $\varphi = \alpha\,(M) + \theta$ where $\theta = 0$, the location of the tip of the cowl and trigonometry. From this point, the Prandtl-Meyer expansion fan is swept backwards as described above, each time calculating the angle the characteristic makes with the x-axis.

Once the slope is known for each characteristic, the Stream Function approximated by a line is employed originating from the end point of the Expansion deflection's contour. Their intersection yields the location of the next point on the contour. These steps are continued until the slope of the characteristic is perpendicular to the flow direction, i.e. the throat. Connecting these calculated points define the Expansion deflection's contour. The accuracy of this technique can once again be evaluated by comparing the isentropic area ratio with the area ratio calculated by the method. As the incremental Prandtl-Meyer expansion angle decreases, the accuracy and smoothness of the contour increases. The technique used in this paper to calculate the contours of the aerospike nozzles are similar to the technique outlined by Lee and Thompson, 1969. For the traditional aerospike nozzle, the technique used in this paper defines the location of the ends of the throat and sets the flow direction at the throat equal to the Prandtl-Meyer expansion angle associated with the desired exit Mach number. Unlike the technique outlined by Lee and Thompson, the calculations used in this paper step forward through the expansion fan by a user-defined Prandtl-Meyer expansion angle increment. The intersection of the characteristics emanating from the expansion point on one

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end of the throat and the Stream Function originating from the last point calculated on the nozzle's contour define the nozzle's contour. The Prandtl-Meyer expansion fan is stepped through until the Mach number along the characteristic being analyzed is greater than or equal to the desired user-defined exit Mach number, in which case, the intersection of the Stream Function and characteristic signify the location of the last point on the nozzle's contour.

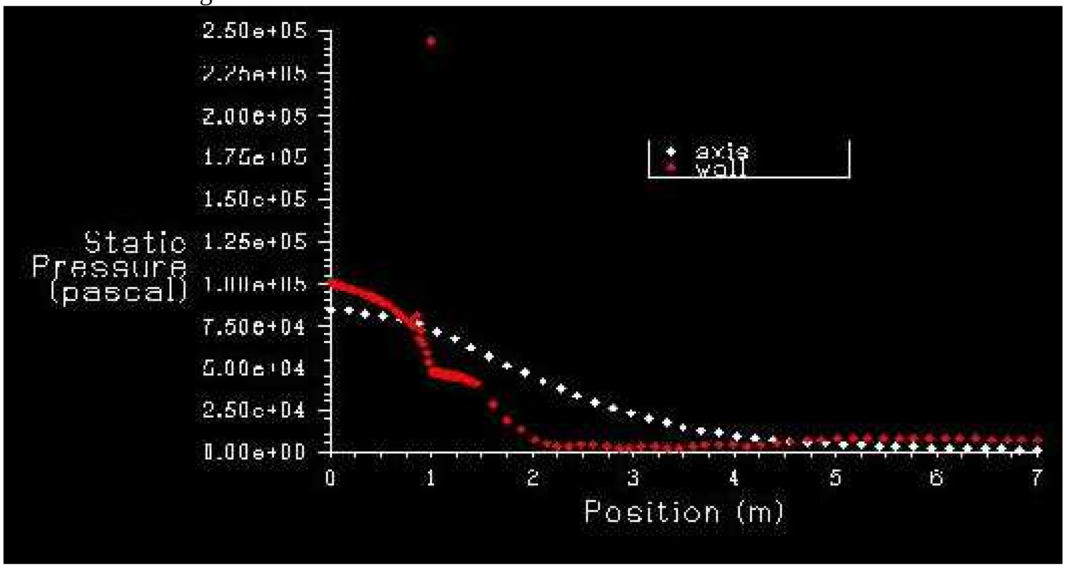
RESULTS AND DISCUSSION

The numerical analysis of conventional bell nozzle and expansion-deflection (ED) nozzle are resulted at different values of pressures and Mach numbers and the corresponding results are compared graphically and discussed.

Comparing the Results of Static Pressure

Comparing the results of conventional bell nozzle with expansion-deflection (ED) nozzle is shown below.

Figure 1.5: Contours of Static Pressure of conventional bell nozzle



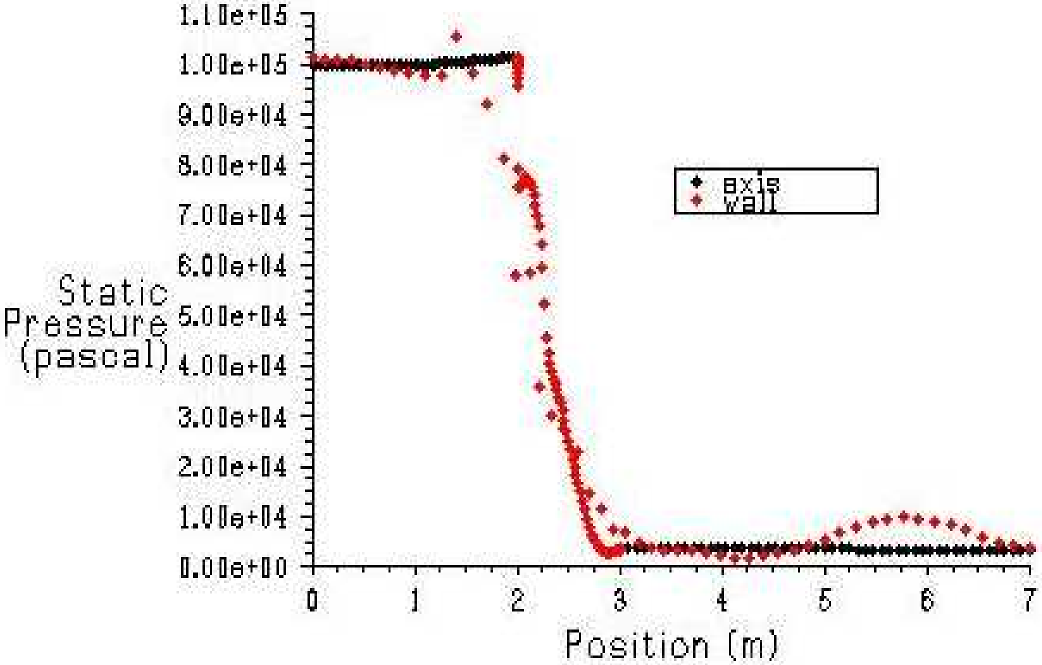


Figure 1.6 : Contours of Static Pressure of expansion-deflection (ED) nozzle

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Comparing the Results of Mach number

Comparing the results of conventional bell nozzle with expansion-deflection (ED) nozzle is shown below.

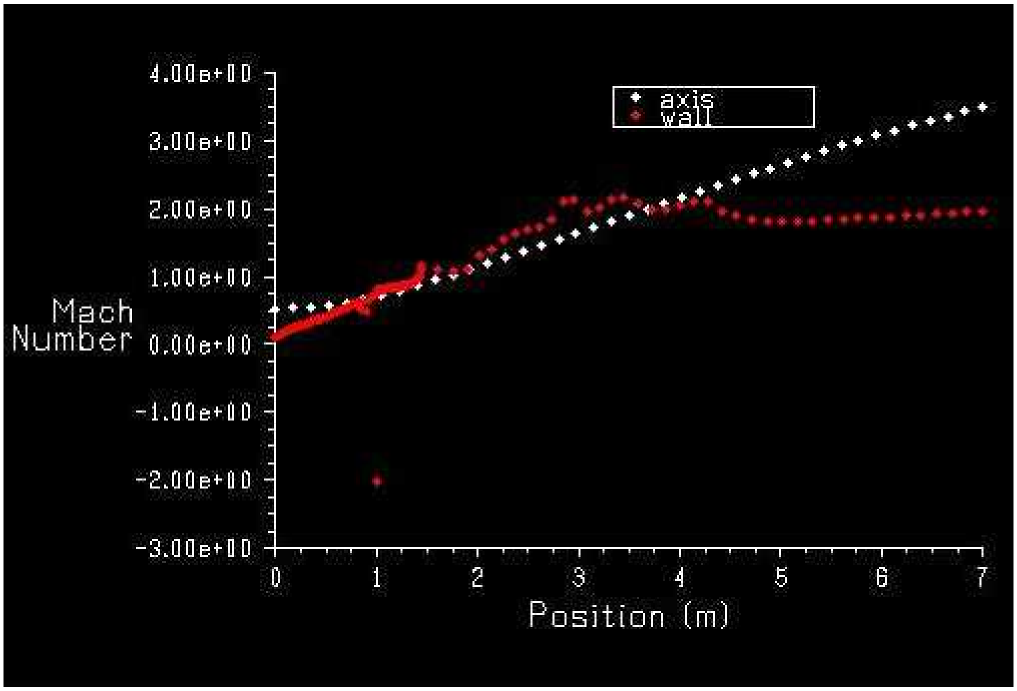

Figure 1.7 : Contours of Static Pressure of conventional bell nozzle

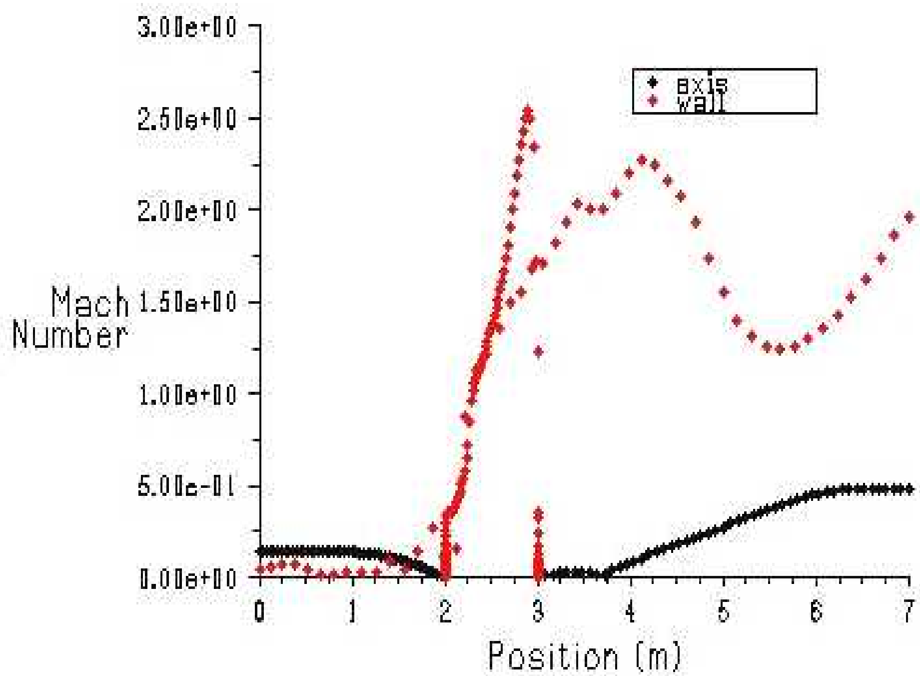

Figure 1.8 : Contours of Static Pressure of expansion-deflection (ED) nozzle

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Comparing the Results of Velocity vectors

Comparing the results of conventional bell nozzle with expansion-deflection (ED) nozzle is shown below.

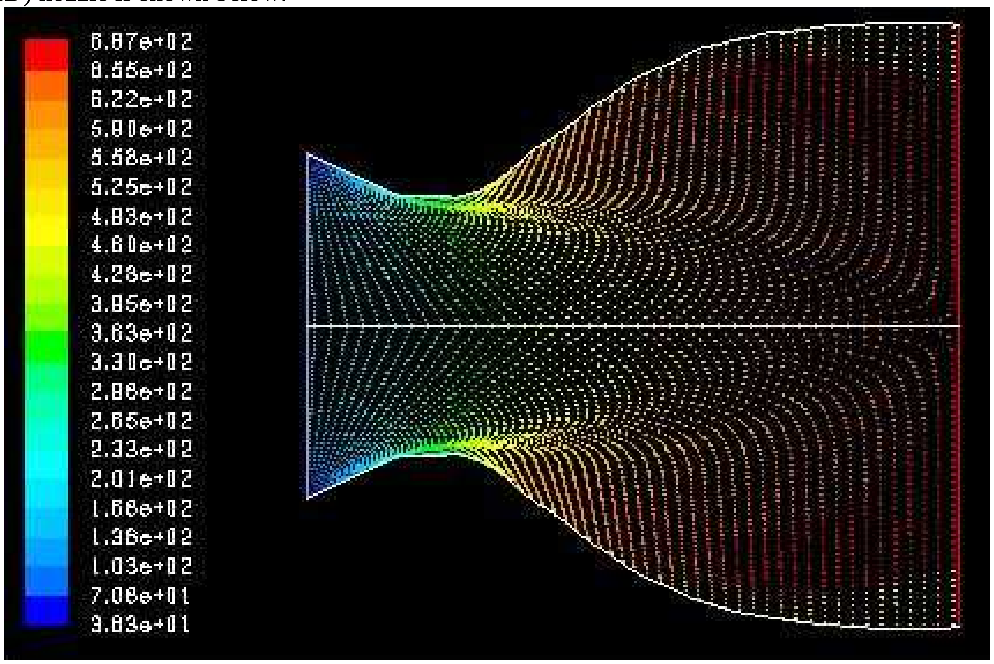

Figure 1.9 : Velocity vectors coloured by velocity magnitude of conventional bell nozzle

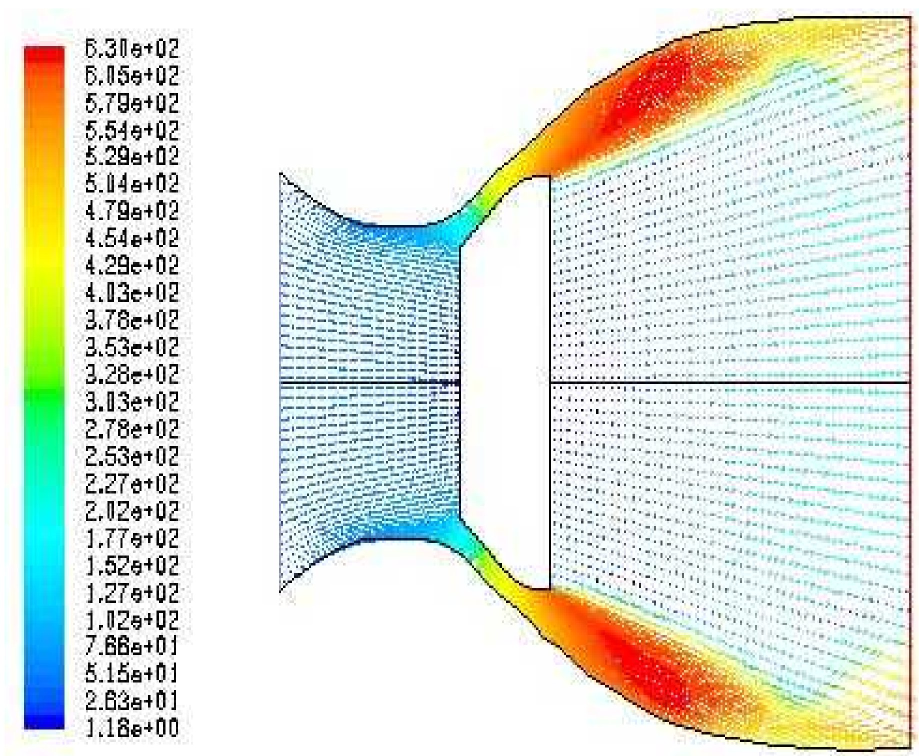

Figure 1.10 : Velocity vectors coloured by velocity magnitude of expansion-deflection (ED) nozzle

DISCUSSION

By comparing the results of conventional bell nozzle with expansion-deflection (ED) nozzle,

Total Pressure values from Figures 6.1. and Figure 6.2.

Conventional bell nozzle	Expansion-deflection (ED) nozzle
Minimum = 1.41Pa	Minimum= 2.5×10^3Pa
Maximum = 10.63Pa	Maximum= 3.31×10^5Pa

Observing the values of total pressure, Expansion-deflection (ED) nozzle has more pressure at same conditions of operation.

Static Pressure values from Figures 6.3. and Figure 6.4.

Conventional bell nozzle	Expansion-deflection (ED) nozzle
Minimum = 5.76×10^2Pa	Minimum = 1.45×10^3Pa
Maximum = 2.44×10^5Pa	Maximum = 1.93×10^5 Pa

Observing the values of static pressure, Expansion-deflection (ED) nozzle has low change of static pressure when compared to Conventional bell nozzle at same conditions of operation.

Mach number values from Figures 6.5. and Figure 6.6.

Conventional bell nozzle	Expansion-deflection (ED) nozzle
Minimum = -2.02	Minimum = -1.01
Maximum = 4.14	Maximum = 10.15

Observing the values of Mach number, Expansion-deflection (ED) nozzle has very high values of Mach number when compared to Conventional bell nozzle at same conditions of operation.

Total Temperature values from Figures 6.5. and Figure 6.6.

Conventional bell nozzle	Expansion-deflection (ED) nozzle
Minimum = 2.98×10^2 K	Minimum =3×10^2 K
Maximum = 3.13×10^2 K	Maximum = 3.14×10^2 K

Observing the values of Total Temperature, Expansion-deflection (ED) nozzle has almost same values of Total Temperature when compared to Conventional bell nozzle at same conditions of operation.

In reaming figures a set of results shown that Expansion-deflection (ED) nozzle has a good correlation with conventional bell nozzle and ED nozzle showing very good performance characteristics at same operating conditions.

CONCLUSION

In this thesis flow structure and the performance of the designed nozzles at different conditions, which are selected hypothetically to represent under-expansion, ideal, and over-expansion conditions, are simulated using ANSYS FLUENT and the results are compared and analyzed. The results clearly indicate that the Expansion deflection nozzle is capable of producing the optimum performance at different flow regimes; this phenomenon is called as the altitude compensation effect. Based on the observed behaviour of the exhaust flow, it can be concluded that the Expansion deflection nozzle is recommended. Because its flow pattern shows the signs of optimum performance and it has achieved the desired exit Mach number in all the three altitude conditions.

SCOPE FOR FUTURE STUDY

From the study and simulation results it is felt that, future studies may be conducted as mentioned below.

- Effect of the base-bleed introduction on the flow pattern and the performance of the Expansion deflection nozzle are yet to be studied.
- Research is needed to study the slip-stream effect of the Expansion deflection nozzle in the sonic and sub-sonic conditions.

REFERENCES

1. N. V. Taylor, C. M. Hempsell, J. Macfarlane et al., "Experimental investigation of the evacuation effect in expansion deflection nozzles," Acta Astronautica, vol. 66, no. 3-4, pp. 550–562, 2010.
2. G. V. Rao, "Recent developments in rocket nozzle configurations," ARS Journal, vol. 31, no. 11, pp. 1488–1494, 1961.
3. G. V. R. Rao, "Analysis of a new concept rocket nozzle," Journal of Liquid Rockets and Propellants, vol. 2, pp. 669–682, 1960.
4. E. L. Morrisette and T. J. Goldberg, "Turbulent flow separation for over expanded nozzles," NASA Technical Paper 1207, 1978.
5. J. Ostlund, Supersonic flow separation with application to rocket engine nozzles [Ph.D. thesis], Royal Institute of Technology, Stockholm, Sweden, 2004.
6. M. Onofri and F. Nasuti, "The physical origins of side loads in rocket nozzles," in Proceedings of the 35th Joint Propulsion Conference and Exhibit, AIAA, Los Angeles, Calif, USA, 1999.
7. G. Hagemann, M. Frey, and D. Manski, "A critical assessment of dual-bell nozzles," in Proceedings of the 33rd Joint Propulsion Conference and Exhibit, 3299, p. 3297, Seattle, Wash ,USA, 1997.
8. G. Doig, T. J. Barber, E. Leonardi, A. J. Neely, H. Kleine, and F. Coton, "Aerodynamics of a supersonic projectile in proximity to a solid surface," AIAA Journal, vol. 48, no. 12, pp. 2916–2930, 2010.
9. G. Hagemann, R. Schwane, P. Reijasse, and J. Ruf, "Nato TRO WG 10—CFD results of plug nozzle test cases," in Proceedings of the 38th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, AIAA 2002-4036, Indianapolis, Ind, USA, 2002.
10. T. J. Mueller, "Determination of the turbulent base pressure in supersonic axisymmetric flow," inProceedings of the 3rd Propulsion Joint Specialist Conference, AIAA paper 67-446, Washington, DC, USA, 1967.