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Analysis of Flow Structure by Varying Divergence Angle and Contour of Supersonic C-D Nozzles

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***Abstract*— The shock formation in rocket engine nozzles have been a significant area of study for researchers. The oblique shock formation has an adverse effect on the efficiency of nozzles. Here a CFD analysis of three contour nozzles with change in divergence angle was conducted using ANSYS Fluent. Supersonic jets emanating from a chocked, axi-symmetric nozzle at different pressure ratios are analyzed here. The variation of shock structure with change in divergence angle is studied. While varying the geometry the length and area ratio of nozzles was kept constant. Care was taken to keep the nozzle exit angle zero degree. No shock free condition was observed even at design Mach number of M=1.5. Simulation has been done on a clear conical nozzle of divergence angle of 2.950, contour nozzles of divergence angles 40 and 50 respectively. The increase in divergence has shown considerable effect in flow properties. The pressure variation along center line was low for high divergence angle. The better design among the three was analyzed by comparing the static pressure, Mach number and density variation along the center line. These flow parameters were compared for two different pressure ratios. The contour nozzle with divergence angle 50 was found to be the best among the three in design. The axial velocity at the exit was compared among them the nozzle with highest divergence angle had higher axial velocity at exit, so it was inferred that the thrust exerted on the walls was higher. By analyzing the flow characteristics the nozzle with high divergence angle showed improved results.**

***Keywords*— Convergent-divergent nozzle, Mach number, shock wave, oblique shock**

I.INTRODUCTION

Thrust is generated due to the change in flow direction through nozzle. Extensive studies have been conducted to explore the wide range of nozzles. As the thrust imparted on the nozzle wall is a function of geometry of the nozzle large varieties of nozzles are investigated. The flow may be sub-sonic, sonic, or supersonic at the exit. It is determined based on the inlet pressure and nozzle geometry. Nozzle can be convergent or convergent-divergent type. The different types of Convergent-Divergent(cd) nozzles or de Laval nozzle geometries are bell nozzle, conical nozzles, spike nozzles, annular nozzles, etc. while designing each of these nozzles certain geometrical considerations has to be followed. Due to the ease of construction conical nozzles were commonly used in rocket applications. It has a small angle and can produce greater thrust. The axial velocity at the exit is maximized and as a result high specific impulse is imparted here. But length and weight is comparatively higher. Bell nozzle is a commonly used contour nozzle and it has significant advantage over conical nozzle. It is better in performance relative to size. The major disadvantage of bell nozzle is that the nozzle must be contoured to restrict oblique shocks and maximize performance.

A rocket engine nozzle is used to direct all the combustion gases and is accelerated at its throat, finally leaves at the exit. The bell shape has a large expansion angle after the throat for the exit gases to leave. Sometimes the contour of the bell nozzles looks complex. There is a quick expansion shock wave generation at the sudden expansion section near the throat. Generation of compression shock waves occurs due to the reversal of slope to zero degrees at the exit. The expansion and compression set of shock waves coincide and cancel each other in a properly designed nozzle. In this way an optimum bell nozzle can be designed with minimum weight and maximum performance. An efficient nozzle can be obtained when the exit pressure equals atmospheric pressure. As the pressure varies with altitude, nozzle design is losing its efficiency and it is optimal only at one altitude.

It is relevant that the convergent-divergent nozzles when operated under off-design conditions produce semi-periodic shock diamonds, shocks and Prandtl-Meyer fans[1]. If the nozzle exit pressure matches the ambient pressure a shock free condition is expected to obtain in the case of a well-designed nozzle. But in practical cases no shock free condition is obtained. Experimental analysis with a conical nozzle captured a double diamond shaped jet plumes along the center line axis[1]. The strength of the shock cell created during the off-design conditions can be studied using optical methods such as particle image velocimetry and schlieren image set-up. Studies reveal that the shock structure are found to be more pronounced at higher Mach numbers[2]. The flow characteristics of supersonic nozzles can be obtained by numerical simulations solving the Navier-Stokes equations. Compared to conical nozzles, contour nozzles especially bell nozzles gives uniform flow at the exit[3]. Flow through a cd nozzle can result in under-expanded, fully expanded(design condition) or over-expanded conditions. Over-expanded occurs when the exit pressure becomes lower than ambient pressure. At over-expanded off-design conditions shock induced boundary layer separation occurs[4]. Both these effects shock and boundary layer separation is not favourable. Usually shocks appear as train structures, repeated after the first shock called shock trains[5]. In numerical simulations choosing the correct turbulence model of the flow is significant. The SST k-ω turbulence model gives better results for axisymmetric mean flow parameters[6][7]. The governing conditions for optimum thrust are the nozzle length, ambient pressure and flow conditions in the immediate vicinity of the throat[8].

It is found that the geometry and design of the C-D nozzle has significance in controlling thrust efficiency. Conical nozzle is the simplest design contour applicable which was used early in rocket engines. Better improvement in thrust can be obtained using a bell nozzle. The contour of bell nozzle is complex compared to conical nozzles for a designer. Studies relating to variation in divergence angle of conical nozzles reveal that for higher cone angles the thrust imposed on walls increases as the design approaches that of a bell nozzle. Nozzle exit angle is significant in determining the efficiency of the system. As the exit angle approaches near zero values the y-component of exit velocity become negligible. Improvement in thrust efficiency can be obtained by properly the nozzle contour.

II. METHODOLOGY

Creation of geometry

The geometry of the C-D nozzle was created using the co-ordinate data obtained. Apart from that additional two nozzle geometries were created by two arc method, slightly varying the divergence angle just after the throat. Geometrical contours of three nozzles with divergence angle 2.95 degree(actual conical nozzle), 4 degree and 5 degree was created in GAMBIT software.

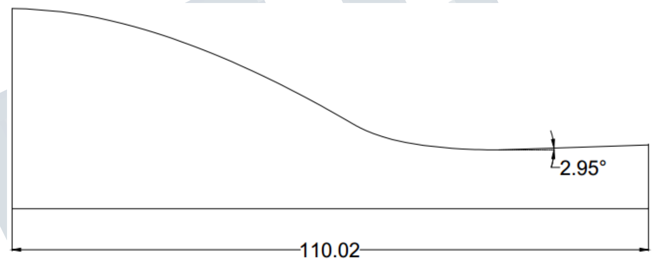

Fig. 1 Conical nozzle with divergence angle 2.95^0

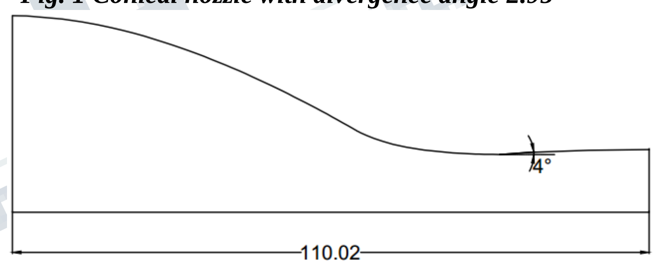

Fig. 2 Conical nozzle with divergence angle 4^0

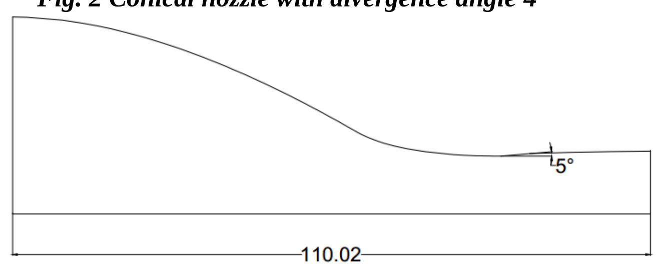

Fig. 3 Conical nozzle with divergence angle 5^0

Table 1 Design parameters of the nozzle.

Design Parameters	Values
Throat Radius, R_{th}	10 mm
Exit Area, a_e	369.836 mm^2
Exit Area Ratio, a_e/a_{th}	1.177225
Nozzle exit Mach number, M_e	1.5

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Nozzle exit pressure, p_e	101325 Pa

Grid generation

The meshing of the domain was done using GAMBIT and the grid chosen to run the simulations had 494315 quadrilateral cells, with 497607 nodes. The complete geometry was divided into 17 faces. The domain was taken 30D along X-direction and 5D along Y-direction. The boundary layer mesh was given adjacent to the walls to capture the flow fields accurately. The first row size a, was given as 0.000638514, with a growth factor 0f 1.2 upto 32 cells. There was a total of 77 nodes along y-direction at interior of the nozzle.

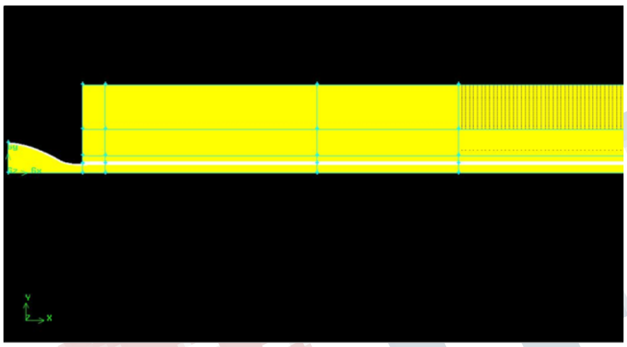

Fig. 4 Meshed model of the conical nozzle

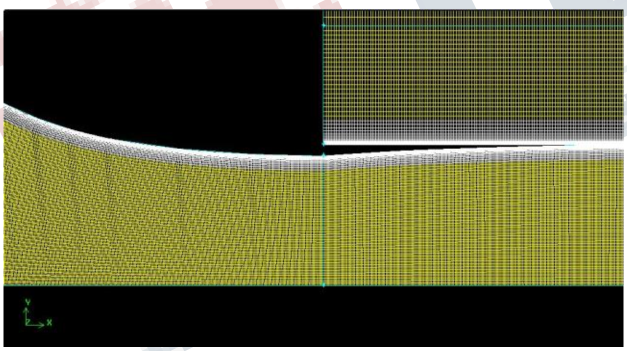

Fig. 5 Boundary layer mesh of the conical nozzle

III. RESULTS AND DISCUSSION

First the models are meshed, imported and flow analysis is carried out in major three steps, the first step is geometry creation and meshing using GAMBIT where the model is drawn, boundaries are created and corresponding boundary conditions are assigned to the boundaries. The second step is 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. The third step is FLUENT, where the corresponding contours are created for following major parameters such a Pressure, Density and Mach number.

Contours of static pressure.

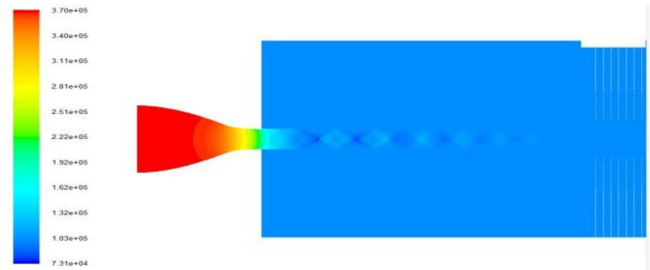

Fig. 6 Static pressure contours of Conical nozzle with divergence angle =2.95^0, NPR=3.7.

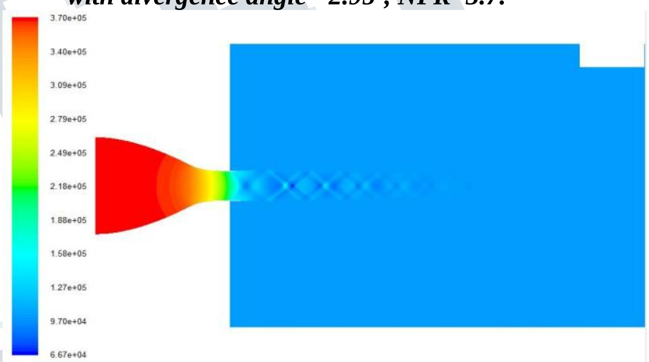

Fig. 7 Static pressure contours of nozzle with divergence angle =4^0, NPR=3.7.

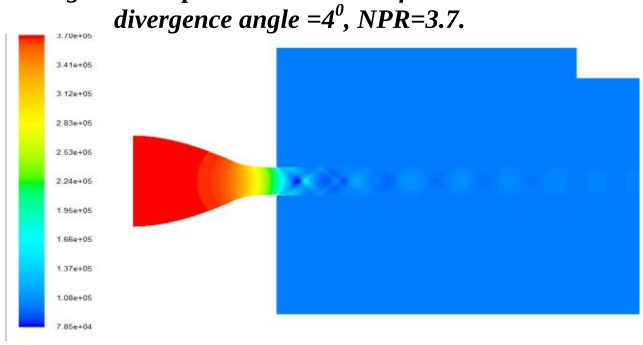

Fig. 8 Static pressure contours of nozzle with divergence angle =5^0, NPR=3.7.

The above figures, Fig. 6, Fig. 7, Fig. 8 shows the static pressure variation of the three conical nozzles with constant NPR of 3.7. The pressure varies in the range 370000 Pa to 66700 Pa. The results shows that on increasing divergence angle the pressure variation decreases. A double shock layer was observed in conical nozzle of divergence angle 4 degree. This layer dies out as divergence angle increases. No shock free condition was observed. Even at the design value of NPR=3.7, shock waves are formed.

The figures Fig. 9, Fig 10, Fig. 11 shows the static pressure contours of the discussed nozzles at under-expanded condition of NPR=5. The pressure varies in the range 500000 Pa to 21200.the shock formation can be clearly visualized by the abrupt changes in pressure along the axis.

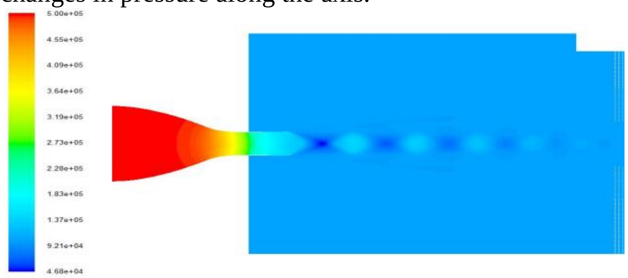

Fig. 9 Static pressure contours of Conical nozzle with divergence angle =2.95^0, NPR=5.

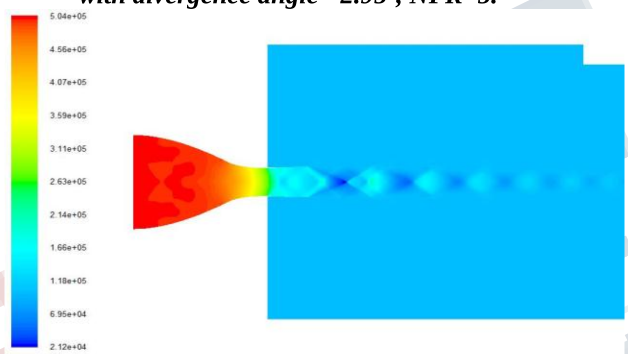

Fig. 10 Static pressure contours of nozzle with divergence angle =4^0, NPR=5.

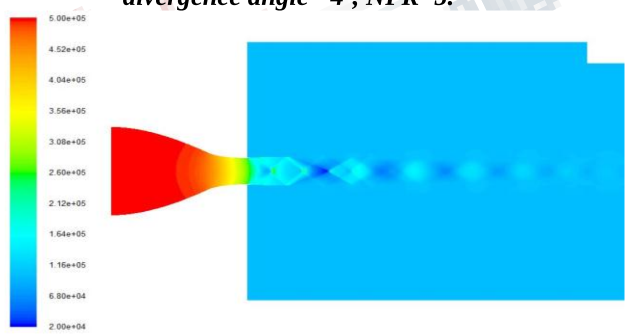

Fig. 11 Static pressure contours of nozzle with divergence angle =5^0, NPR=5.

Contours of Mach number.

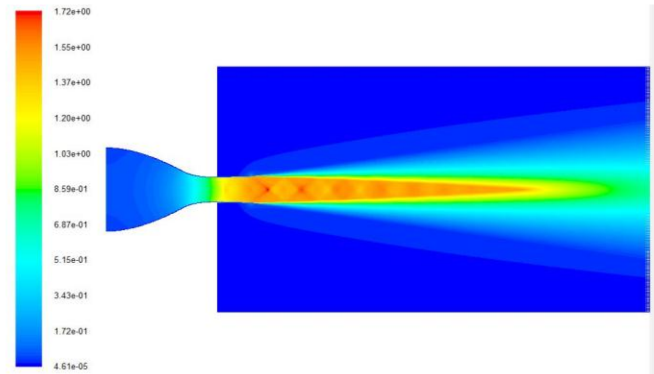

Fig. 12 Mach number contours of Conical nozzle with divergence angle =2.95^0, NPR=3.7.

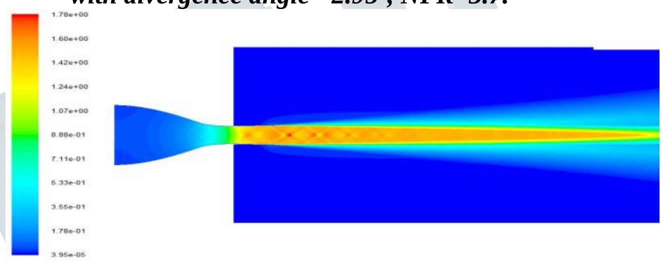

Fig. 13 Mach number contours of nozzle with divergence angle =4^0, NPR=3.7.

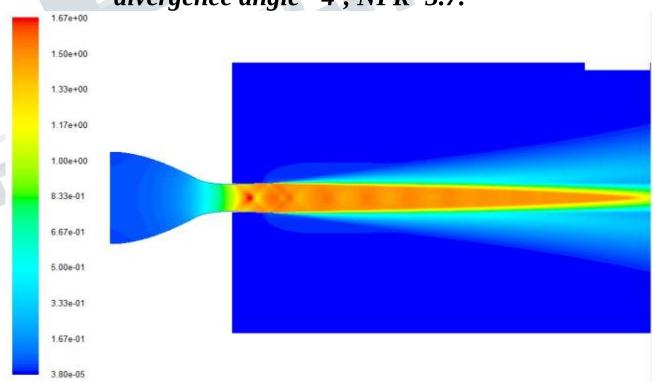

Fig. 14 Mach number contours of nozzle with divergence angle =5^0, NPR=3.7.

The contours of Mach number for various divergence angles for the design NPR of 3.7 are shown. The highest Mach number value reached at the exit for conical nozzle of divergence angle 2.95 was 1.72 but it was slightly higher for 4 degree divergence angle.

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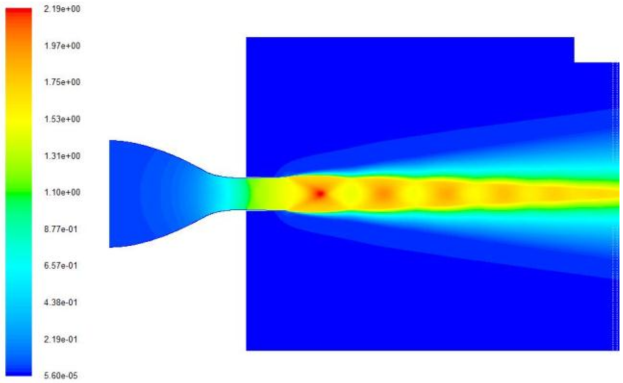

Fig. 15 Mach number contours of conical nozzle with divergence angle =2.95^0, NPR=5.

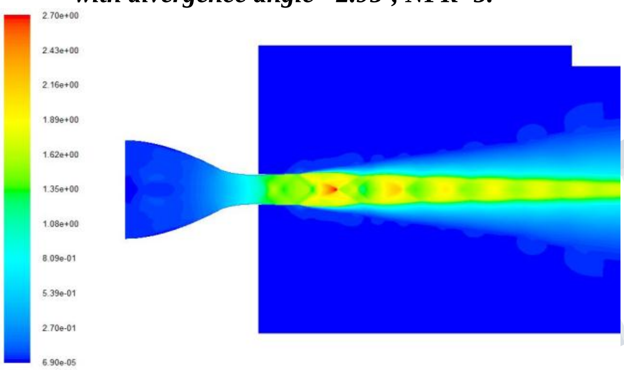

Fig. 16 Mach number contours of nozzle with divergence angle =4^0, NPR=5.

After analyzing the Mach number contours of underexpanded condition of NPR=5, it can be found out that the Mach number increases on increase in divergence angle. With conical 2.95^0 the highest mach number reached was 2.19 but for divergence angle of 4^0 it reached to 2.7.

C. Static pressure plot comparison.

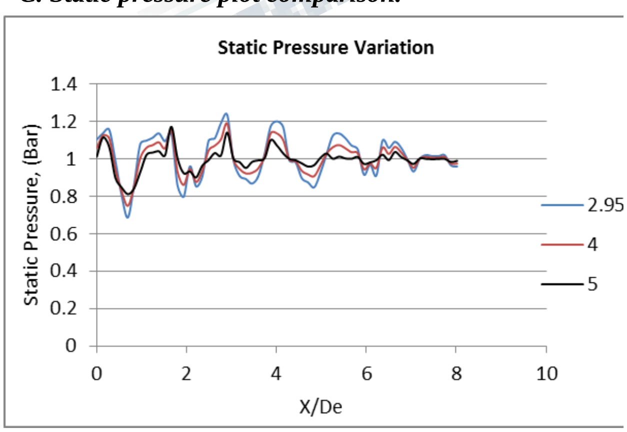

Fig. 17 Static pressure variation at different divergence angles at NPR = 3.7.

The fig. 17 shows the static pressure variation of conical nozzles with three different divergence angles at design NPR of 3.7. We can notice that the pressure varies abruptly about the mean pressure line. The sudden variation of pressure on both sides indicates the presence of shock waves. The maximum pressure point of conical nozzle (having divergence angle 2.95^0) is 1.23 bar, while the maximum pressure obtained for conical nozzle having divergence angle 4^0 is 1.18 bar and for divergence angle 5^0 it was found to be 1.14 bar. From the above graph it can be clearly observed that with increase in divergence angle the pressure variation is low. The strength of the shocks decreases as divergence angle increases. The variation of pressure was higher for lowest divergence angle, the shock waves are intense for this zone so the thrust exerted on the nozzle walls are lower.

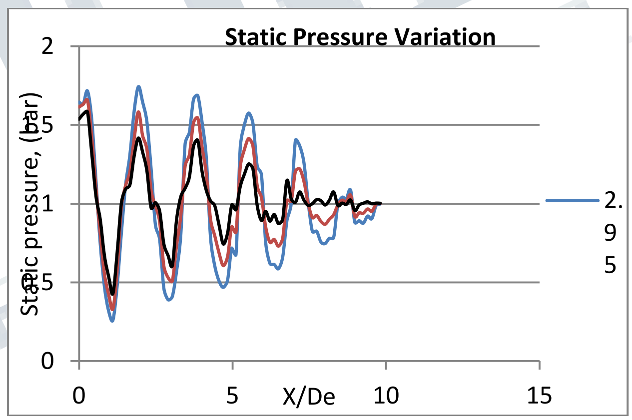

Fig. 18 Static pressure variation at different divergence angles at NPR = 5.

The static pressure variation of conical nozzles with divergence angles 2.95^0, 4^0 and 5^0, at underexpanded condition of NPR=5 is shown. As discussed earlier the pressure variation is least for higher divergence angle. Here the maximum pressure reached for conical nozzle of divergence angle 2.95^0 is 1.74 bar, in the case of 4^0 divergence angle it was 1.58 bar and for the highest divergence angle 5^0 it was 1.41 bar. The minimum pressure values reached were 0.26 bar, 0.34 bar and 0.44 bar for divergence angles 2.95^0, 4^0 and 5^0 respectively. As the pressure variation is least for 5^0 divergence angle the strength of the shock wave formed may be lesser. Analyzing the static pressure values for both the cases nozzle having higher divergence angle was found to be a better design.

Mach number plot comparison.

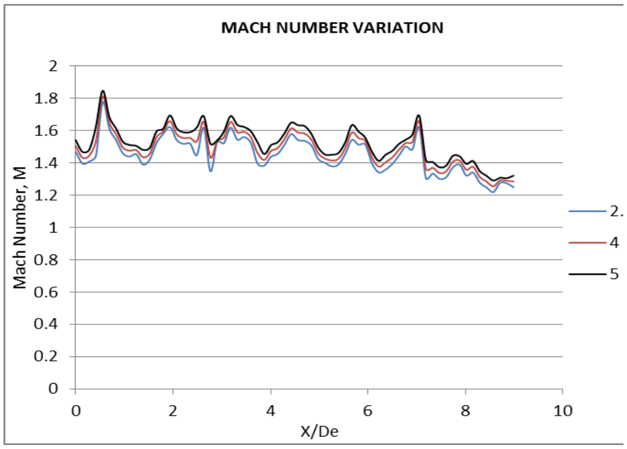

Fig. 19 Mach Number variation at different divergence angles for NPR = 3.7.

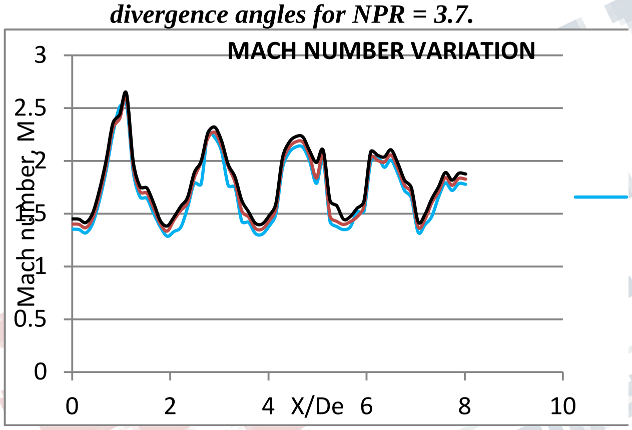

Fig. 20 Mach Number variation at different divergence angles for NPR = 5.

The Mach number plots of the nozzles with divergence angles 2.95^0, 4^0 and 5^0 at two different NPR values 3.7 and 5 are shown. The highest value of mach number at exit reached for 5^0 divergence angled nozzle is 1.83, in the case of conical nozzle with divergence angle 4^0 it was 1.81, the value reached 1.79 for the conical nozzle with least divergence angle. The variation of values of Mach number was non-uniform due to the formation of shock waves. Mach number at exit was higher for higher divergence angle. It was highest for conical nozzle having divergence angle of 5^0 and was lowest for nozzle with divergence angle 2.95^0. Here also the better design option was the one with higher divergence angle.

Variation of axial velocity.

The axial velocity at exit of the nozzle is significant in determining the thrust imposed on the nozzle. If the axial component of velocity is higher it promotes to better efficiency. The axial velocity varies abruptly along the centre line of the nozzle. Then it attains a mean value for certain distance and again it decreases. The average axial velocity value is taken as the mean value which attains through a certain distance. The average axial velocity value for conical nozzle of divergence angle 2.95^0 was found to be 467 m/s, in the case of conical nozzle with divergence angle 4^0 it was 476 m/s and for the highest divergence angle it was obtained to be 483 m/s. From this analysis we can infer that the axial velocity increases with increase in divergence angle for a conical nozzle. As the axial component of velocity increases the thrust exerted on the walls of the nozzles raises. From this discussion it is very much clear that better performance and efficiency can be obtained from a conical nozzle with high divergence angle.

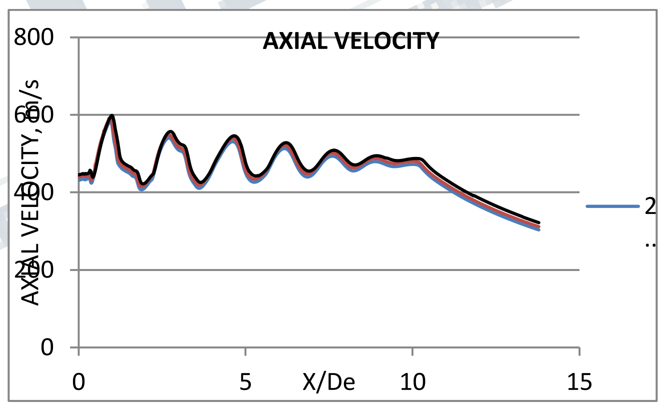

Fig. 21 Axial velocity of nozzles for various divergence angles at NPR = 5.

IV.CONCLUSION

Design of nozzle geometry is an important area in the field of rocket propulsion. Study of flow and analysis of shock structure is considered core here. Nozzle design and its effect on a rocket engine efficiency is another issue considered in this study. The flow structure of convergent-divergent nozzles at various divergence angle was studied at two different pressure ratios.

The flow parameters such as static pressure and Mach number was compared with three different nozzle divergence angles 2.95^0, 4^0 and 5^0. Analyzing the plots of static pressure it is found that with increase in divergence angle the pressure variation is low. The strength of the shocks decreases as divergence angle increases. The variation of pressure was higher for lowest divergence angle, the shock waves are intense for this zone so the thrust exerted on the nozzle walls are lower. Analyzing the static pressure values for both the cases nozzle having higher divergence angle was found to be a better design.

The average axial velocity value for conical nozzle of divergence angle 2.95^0 was found to be 467 m/s, in the case of contour nozzle with divergence angle 4^0 it was 476 m/s and for the highest divergence angle it was obtained to be 483 m/s. Here we can infer that the axial velocity increases with increase in divergence angle for a nozzle. As the axial component of velocity increases the thrust exerted on the walls of the nozzles raises.

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