Flow Analysis of Rocket Nozzle Using Computational Fluid Dynamics (Cfd)

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ABSTRACT

A nozzle is used to give the direction to the gases coming out of the combustion chamber.Nozzle is a tube with variable cross-sectional area. Nozzles are generally used to control the rate of flow, speed, direction, mass, shape, and/or the pressure of the exhaust stream that emerges from them.The nozzle is used to convert the chemical-thermal energy generated in the combustion chamber into kinetic energy. The nozzle converts the low velocity, high pressure, high temperature gas in the combustion chamber into high velocity gas of lower pressure and low temperature.Our study is carried using software's like gambit 2.4 for designing of the nozzle and fluent 6.3.2 for analyzing the flows in the nozzle.Numerical study has been conducted to understand the air flows in a conical nozzle at different divergence degrees of angle using two-dimensional axisymmetric models, which solves the governing equations by a control volume method. The nozzle geometry co-ordinates are taken by using of method of characteristics which usually designed for De-Laval nozzle. The present study is aimed at investigating the supersonic flow in conical nozzle for Mach number 3 at various divergence degree of angle. The throat diameter and inlet diameter is same for all nozzles with various divergence degree of angles. The flow is simulated using fluent software. The flow parameters like pressure , Area of nozzle at exit are defined prior to the simulation.

The result shows the variation in the Mach number, pressure, temperature distribution and turbulence intensity.

Key words —conical nozzle, degree of angle, supersonic flow, Mach number, Control Volume

I. INTRODUCTION

Swedish engineer of French descent who, in trying to develop a more efficient steam engine, designed a turbine that was turned by jets of steam. The critical component – the one in which heat energy of the hot high-pressure steam from the boiler was converted into kinetic energy – was the nozzle from which the jet blew onto the wheel. De Laval found that the most efficient conversion occurred when the nozzle first narrowed, increasing the speed of the jet to the speed of sound, and then expanded again. Above the speed of sound (but not below it) this expansion caused a further increase in the speed of the jet and led to a very efficient conversion of heat energy to motion. The theory of air resistance was first proposed by Sir Isaac Newton in 1726. According to him, an aerodynamic force depends on the density and velocity of the fluid, and the shape and the size of the displacing object. Newton's theory was soon followed by other theoretical solution of fluid motion problems. All these were restricted to flow under idealized conditions, i.e. air was assumed to posses constant density and to move in response to pressure and inertia. Nowadays steam turbines are the preferred power source of electric power stations and large ships, although they usually have a different design-to make best use of the fast steam jet, de Laval's turbine had to run at an impractically high speed. But for rockets the de Laval nozzle was just what was needed.

II. MATERIAL AND METHODS MATHEMATICAL MODEL

A mathematical model comprises equations relating the dependent and the independent variables and the relevant parameters that describe some physical phenomenon. Typically, a mathematical model consists of differential equations that govern the behavior of the physical system, and the associated boundary conditions. To start with fluent, it is necessary to know if the meshed geometry is correct, so is checked. To ensue with, we are to define the model, material, operating condition and boundary condition. Models are to be set in order to define if any energy equation is dealt with our study, if the flow is viscous…etc. We have chosen coupled solver, 2d implicit, absolute velocity formulation, cell based gradient option, superficial velocity porous formulation. As our flow is dealt with energy equation so is necessary to check them up. The material is selected as air and the density as ideal gas to make the solution simpler. Under the solve command the control is selected for limiting the pressure to a maximum of 5e+7 and Minimum of 1e+4. The initialization of value is computed from the inlet. It is also necessary to select the appropriate approximation required in the residual command under monitors and check in plot to visualize the progress of iteration. 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.

III. RESULTS AND DISCUSSION

The geometry of the grid is designed by the help of gambit tool and is made by using of method of characteristics which usually designed for De-Laval nozzle. On the same basic we take the throat co-ordinates and exit co-ordinates for designing this nozzle and after calculating, we get an angle nearly 7. and simulate it using Fluent software and after this we take minimum degree of angle for conical nozzle i.e.7.^{0} and check the variation in Mach Number and other properties to

CASE 1

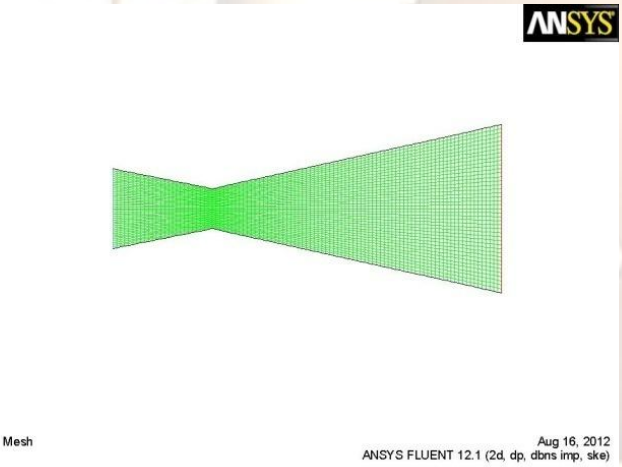

Figure 1:nozzle at 7^0 grid display

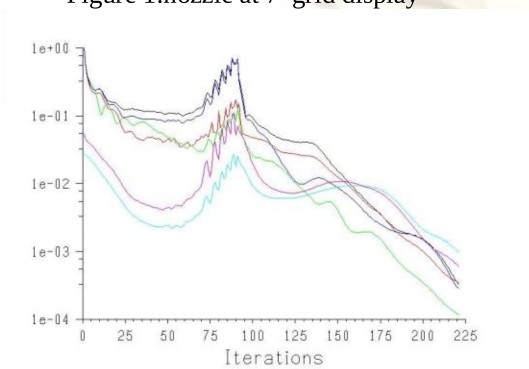

Figure 2:nozzle at 7 residual

The following are the results of nozzle with divergence angle of 7 degrees.

VELOCITY COUNTOUR

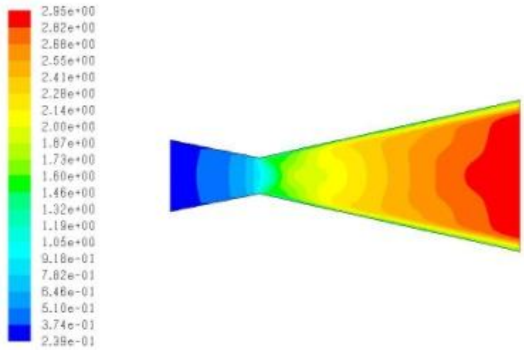

Figure: Velocity Contour For Nozzle With Divergence Angle 7 Degrees.

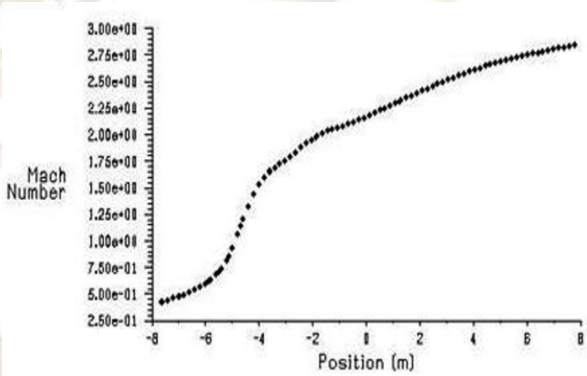

Figure XY Plot for Velocity contours For Nozzle with Divergence Angle of 7 Degrees.

In this, the nozzle is designed for Mach no. 3. From Figure, it is clearly visualized that in the convergent section at inlet point, Mach number, is in the Sub-sonic region (=0.35) while at the throat, flow becomes Sonic (=1.02) and at the nozzle exit it becomes Super-Sonic (=2.90) for which the nozzle is designed. Near the wall, the Mach number is 1.65. This is due to the viscosity and turbulence in the fluid.

From the graph it is clearly observed that the velocity is increased.

STATIC PRESSURE:

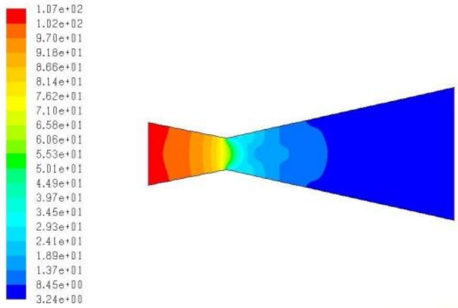

Figure : Static Pressure Contour For Nozzle With Divergence Angle Of 7 Degrees.

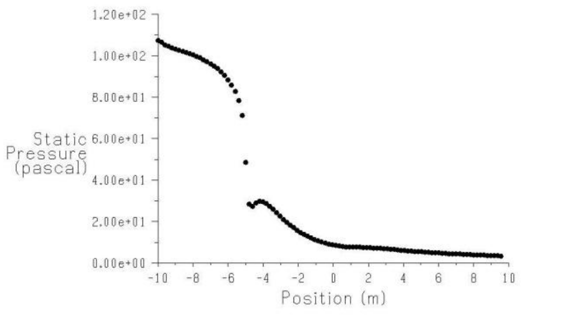

Figure: XY Plot For Static Pressure With Divergence Angl Of 7 Degrees.

Static pressure is the pressure that is exerted by a fluid. Specifically, it is the pressure measured when the fluid is still, or at rest. The above Figure reveals the fact that the gas gets expanded in the nozzle exit. The static pressure in the inlet is observed to be 108 Pa and as we move towards the throat there is a decrease and the value at the throat is found out to be 56 Pa. After the throat, there is sudden expansion and the static pressure falls in a more rapid manner towards the exit of the nozzle. At the exit it is found to be 3.75 Pa.

TOTAL TEMPERATURE

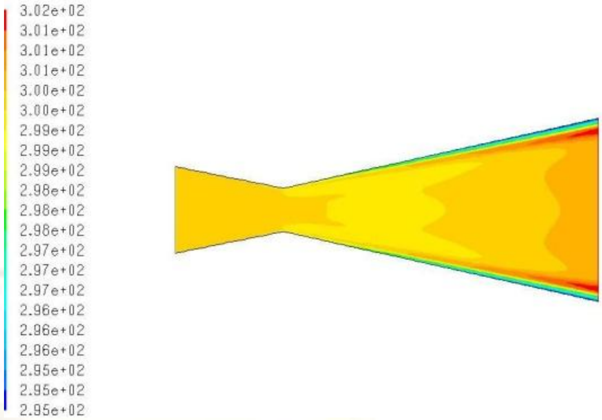

FIGURE: Temperature Contour For Nozzle With Divergence Angle Of 7 Degrees

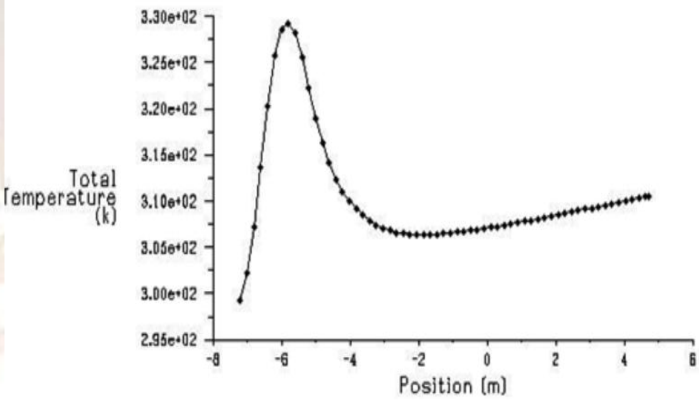

FIGURE : Xy Plot For Total Temperature With Divergence Angle Of 7 Degrees.

The total temperature almost remains a constant in the inlet up to the throat after which it tends to increase. Near the walls the temperature increases to 302 K. In the inlet and the throat the temperature is 300 K. After the throat, the temperature increases to 301K at the exit. As we move from the centre vertically upwards at the exit, there is variation. At the centre it is 300 K, at the walls it is 302 K and moving inward a little bit from the wall the temperature reaches a maximum of 301 K.

Turbulence intensity

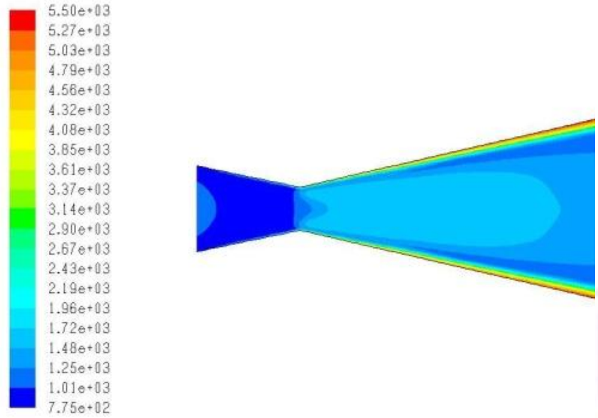

Figure Turbulence Intensity Contour With Divergence Angle Of 7 Degrees

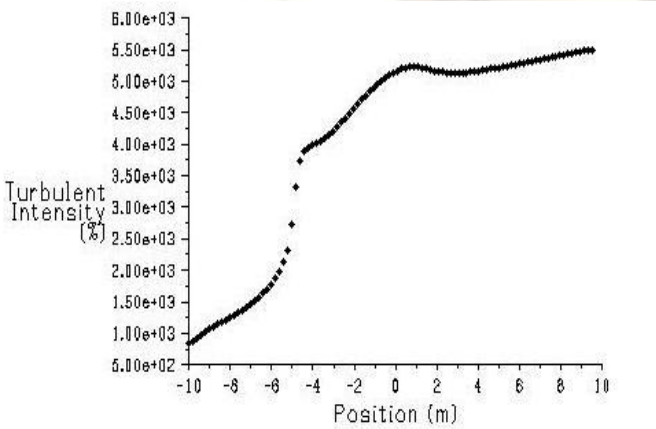

Figure XY Plot For Turbulence Intensity With Divergence Angle Of 7 Degrees.

The turbulent intensity at the convergent section is very low (=1.01e+03 %). Almost till the throat it remains almost a constant. At the throat there is a very small increase to 1.25e+03 %. As soon as it crosses the throat, there is a sudden increase in the turbulent intensity due to the sudden increase in the area. As we move towards the exit, there is a small patch in the centre where the turbulent intensity increases (1.48e+03 %) and then as the fluid stabilizes near the exit, there is a decrease in the turbulent intensity (1.25e+03 %). Near the walls the turbulent intensity is high due to the reversals of flow. At the exit near the walls the turbulent intensity reaches a maximum (=4.56e+03 %).

CASE 2:

The following are the results of nozzle with divergence angle of 20 degrees.

VELOCITY COUNTOUR

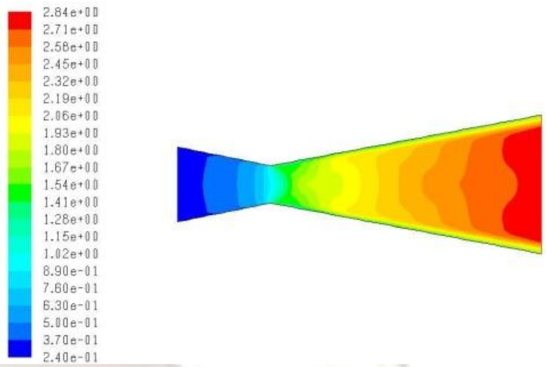

Figure: Velocity contour For Nozzle with Divergence Angle of 20 Degrees

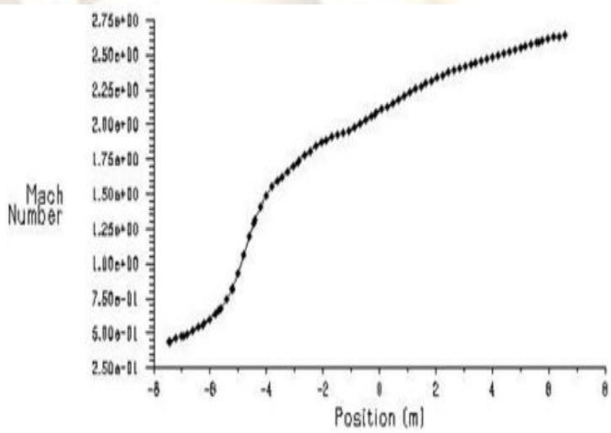

Figure: XY Plot for Velocity contour With Divergence Angle of 20 Degrees

From the Figure, it is clearly observed that Mach number in the convergent section is 0.24 (Sub-Sonic), at the throat it is 1.15(Sonic) and as we move in the divergent section, it keeps increasing and at the exit it is 2.84(Super-Sonic). Parallel flow is observed which is a characteristic of the conical nozzle and its design purpose (for Mach 3) is also solved. Mach number near the wall is less due to the viscosity and the turbulence (=1.54). The Mach number for the default angle turns out to be 2.90 but for a divergence angle of 20 degrees it comes out to be 2.84. This is due to the change in the geometry due to which flow also changes.

STATIC PRESSURE

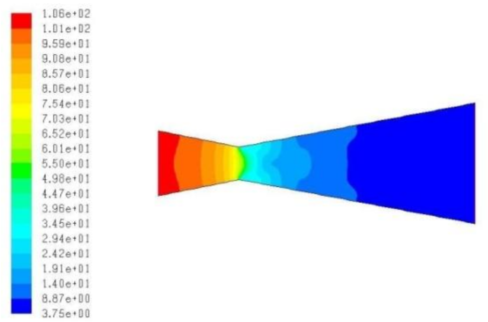

Figure: Static Pressure Contour with Divergence Angle of 20 Degrees

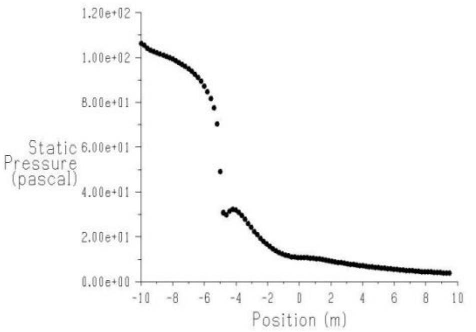

Figure: XY Plot for Static Pressure With Divergence Angle Of 20 Degrees.

The above Figure shows that the gas gets over expanded in the nozzle exit. The static pressure in the inlet is observed to be 106 Pa and the value at the throat is found out to be 65.2 Pa. At the exit the pressure is found to be 8.85 Pa. Right from the inlet to the throat to the exit the static pressure tends to decrease. There is a considerable decrease observed after the throat to the exit where there is a large drop in the static pressure. As compared to the previous case there is a change in the exit static pressure value.

TOTAL TEMPERATURE

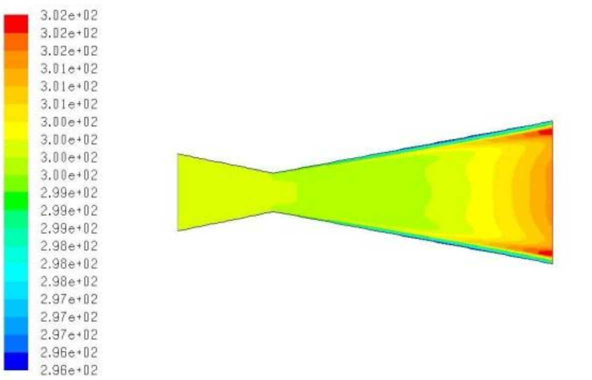

Figure: Total Temperature Contour With Divergence Angle Of 20 Degrees.

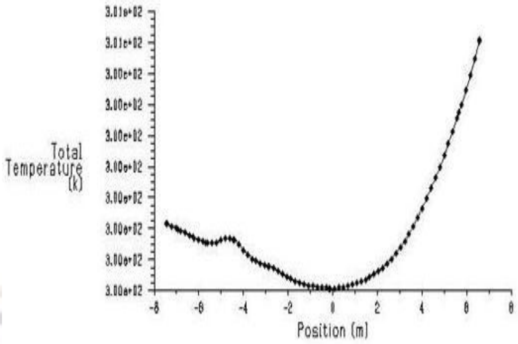

Figure: XY Plot For Total Temperature With Divergence Angle Of 20 Degrees.

The total temperature almost remains a constant in the inlet up to the throat. Increase is observed after some distance from the throat towards the exit as seen in the above Figure Near the walls the temperature decreases to 298 K. In the inlet and the throat the temperature is 300 K. After the throat, the temperature increases to 302K at the exit. At the exit, moving vertically upward there is variation. The maximum value is not attained at the centre but at some distance from the centre. At the centre it is 301 K and at the wall it is 298 K. The maximum value of 302 K is attained near the walls but some distance away from it. There is not much difference in the total temperature contour when compared to the default nozzle but the fact that in the default nozzle, the temperature increases as soon as the throat is crossed but in this it is clearly observed that there is a beginning in the rise in temperature after some distance from the throat.

Turbulence intensity

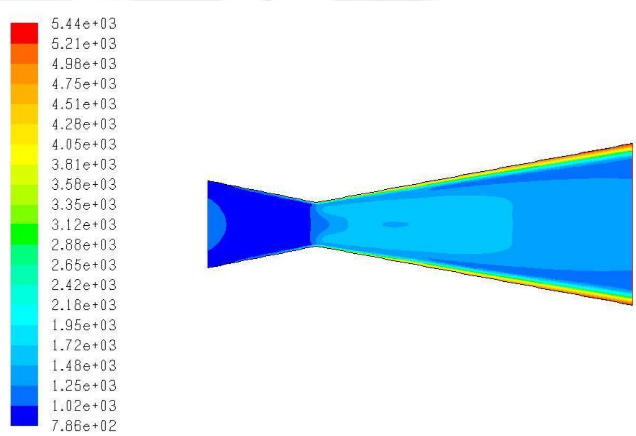

Figure Turbulence Intensity Contour With Divergence Angle Of 20 Degrees.

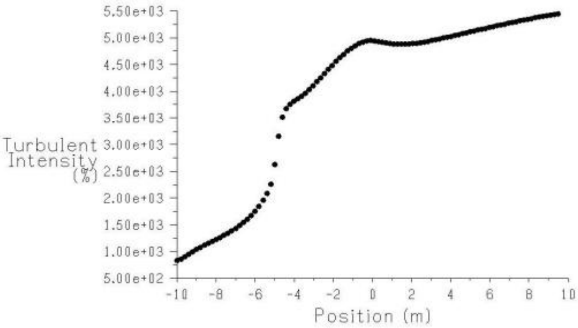

Figure : XY plot for turbulence intensity With Divergence Angle Of 20 Degrees.

The turbulent intensity at the convergent section is 8.17e+01 % which is low. It remains a constant almost up to the throat. At the throat it increases to 8.75e+02 %. Since there is an increase in the area, there is also an increase in the turbulent intensity as we move towards the exit from the throat. There is a difference when compared to the default nozzle. There is a larger increase in the area just after in the default case where as the increase in the area is more gradual in the divergence angle of 7 case. As we move towards the exit, there is a small patch in the centre extending from the throat to almost the centre between the throat and the exit where the turbulent intensity increases (1.93e+03 %) and as we exit there is stabilization of the fluid near the exit of the nozzle (1.67e+03 %). The turbulent intensity reaches a maximum of 4.84e+03 % near the walls as there is reversal of flow and turbulence due to the walls.

CASE 3:
The following are the results of nozzle with divergence angle of 30 degrees.

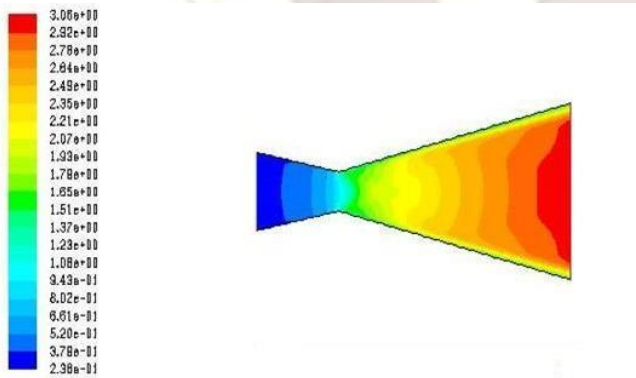

Figure : Velocity Contour With Divergence Angle of 30 Degrees

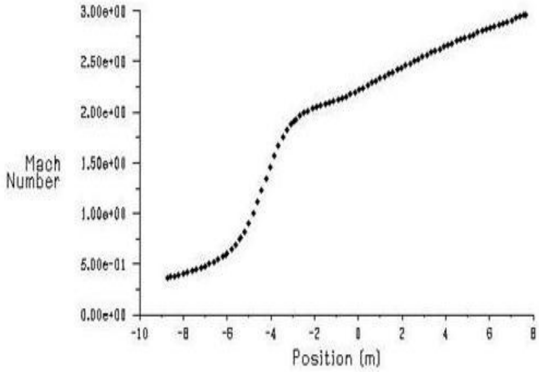

Figure : XY Plot For Velocity contour With Divergence Angle Of 30 Degrees

The region in the inlet is sub-sonic and has an inlet value of 0.23. As it nears the throat it becomes sonic and at the throat it is 1.51 and the exit is super-sonic and it exits with a Mach number of 3.06. The motive of the design of the conical nozzle is also achieved with parallel flow. There are irregularities near the walls due to the reversals of flow. The Mach number as observed in the previous case of divergence angle of 20 degrees was 2.84 which is less than the present case.

STATIC PRESSURE:

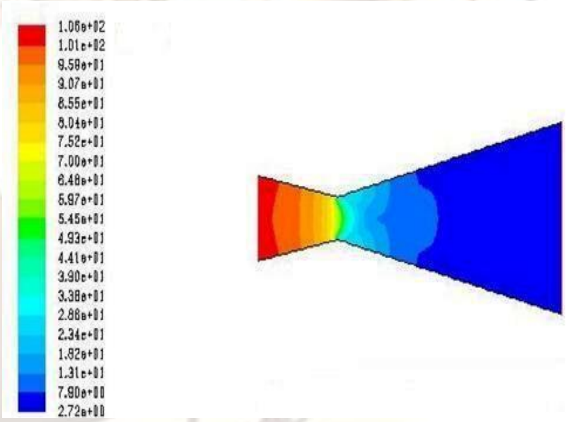

Figure: Static Pressure Contour With Divergence Angle Of 30 Degrees

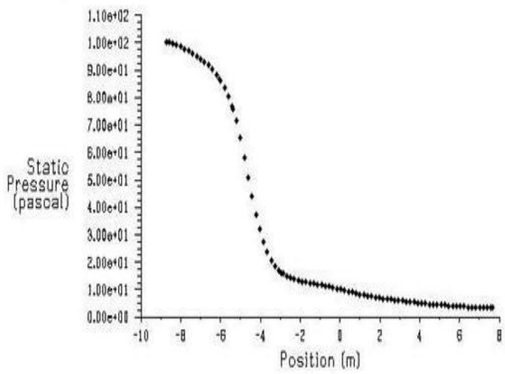

Figure: XY Plot of Static Pressure With Divergence Angle Of 30 Degrees

The static pressure contour is also similar to that of the previous version. It decreases to the throat and then continues to decrease till the exit. The value at the inlet is 106 Pa and at the throat it is 55 Pa. There is also a steep decrease after the throat where the static pressure reduces to 2.72 Pa at halfway around outlet and remains the same till the exit. There is a slight decrease in the minimum value of static pressure from 8.8 to 2.24 pa.

Total temperature:

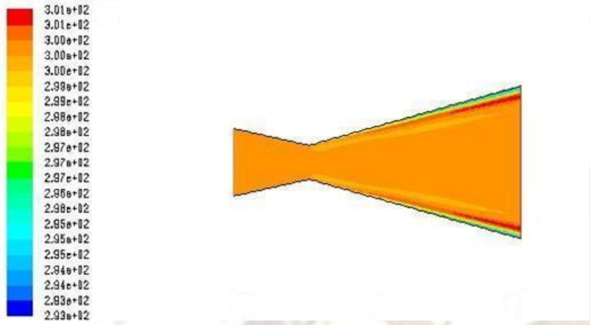

Figure : Total Temparature Contour With Divergence Angle Of 30 Degrees

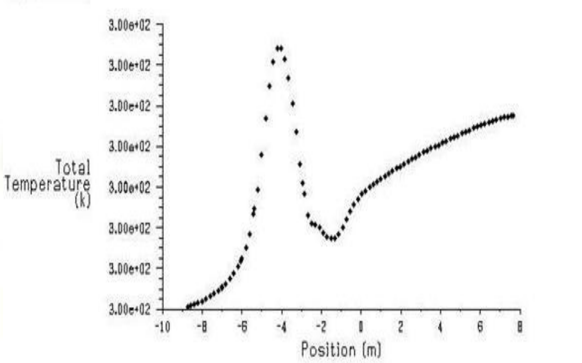

Figure: XY Plot of Total Temperature With Divergence Angle of 30 Degrees

There is a lot of variation in the total temperature plot. In the previous case it was observed that there is an increment in the temperature after the throat and midway from the exit but in this case, there is a difference. Here the temperature tends to increase just after inlet. After this it remains a constant till the exit except near the walls where it increases further and then decreases as we move from the centre to the wall. The value at the inlet is 300 K and then increases near the inlet to 300.25 K. At the throat as well as the exit, the value remains the same. The maximum value attained is 301 K which is, moving vertically from the wall, some distance from it before which the value steeply increases up to the maximum value and then decreases a little. The maximum value has reduced a little by 1 K considering this case and the previous case of divergence angle of 20 degrees.

Turbulence intensity:

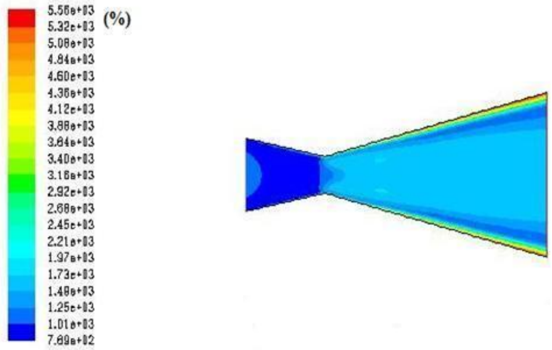

Figure Turbulence Intensity Contour With Divergence Angle Of 30 Degrees

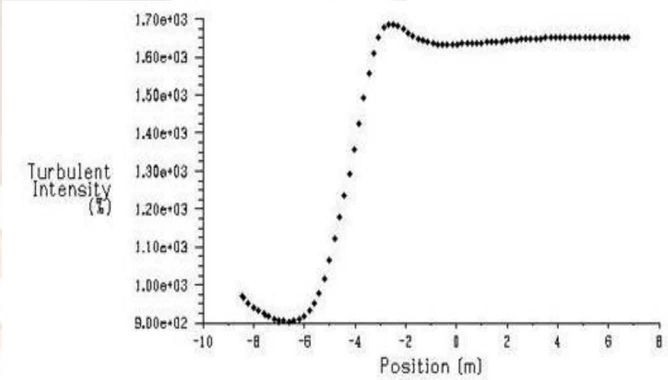

Figure XY Plot of Turbulence Intensity With Divergence Angle of 30 Degrees

The turbulent intensity at the convergent section is 1.01e+03 % which is very low. It remains a constant almost up to the throat. At the throat it increases to 1.25e+03%. There is an increase in the value after the throat as there is a sudden expansion to a bigger area than the nozzle. There is also a difference in the pattern when compared to the 7 nozzle. There were patches in the 1st 2 nozzles (default and 20) but here there are no patches and the flow stabilization which was observed towards the end of the nozzle in the other nozzles is not observed here as the increase is right from the throat to the exit. The maximum value however is reached near the walls as the reversals cause more turbulence. The exit turbulent Intensity value at the centre is 1.49e+03%. Moving vertically upward (or) downward at the exit, at the centre it is 1.49e+03 % which remains a constant up to some distance after which there is a slight decrease to 1.73e+03% and again it decrease after which there is a steep increase up to the wall where it attains a maximum value to 5.32e+03 %. There is an increase in the maximum value when compared to the previous nozzle.

CASE 4:

The following are the results of nozzle with divergence angle of 40 degrees.

VELOCITY COUNTOUR

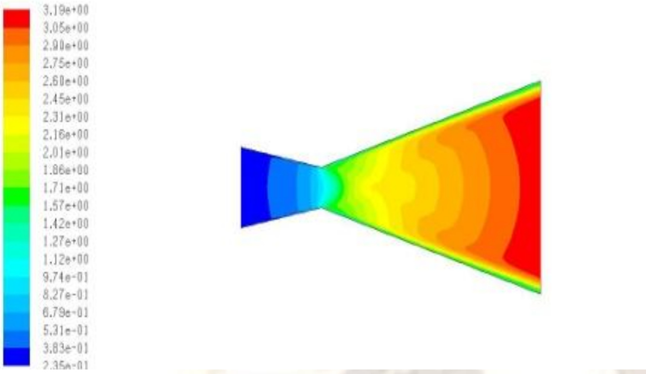

Figure : Velocity Contour With Divergence Angle of 40 Degrees

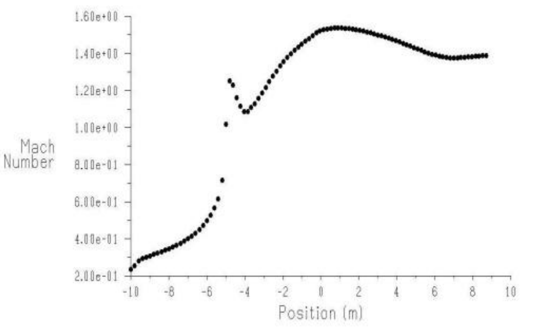

Figure: XY Plot For Velocity contour With Divergence Angle of 40 Degrees

From Figure it can be seen that there is parallel flow. The Mach number at the inlet is 0.383 which is Sub-Sonic, 1.42 at the throat and 3.10 at the exit. There is a decrease in the value of Mach number near the walls. Its value is 1.71. Turbulence and viscosity are the cause for this decrease. The Mach number has increased in this case to 3.10 where as it was 2.84 in the case of divergence angle of 30 degrees.

TOTAL TEMPERATURE

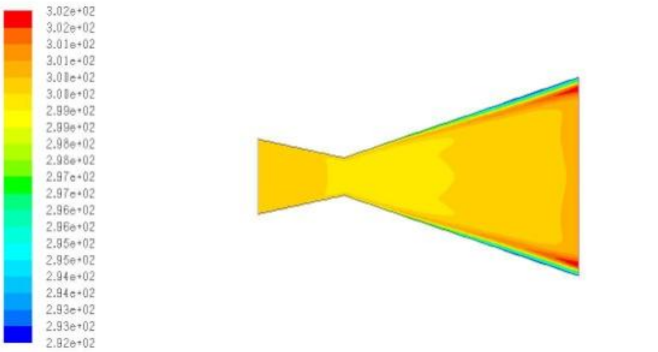

Figure: Total Temperature Contour With Divergence Angle of 40 Degrees

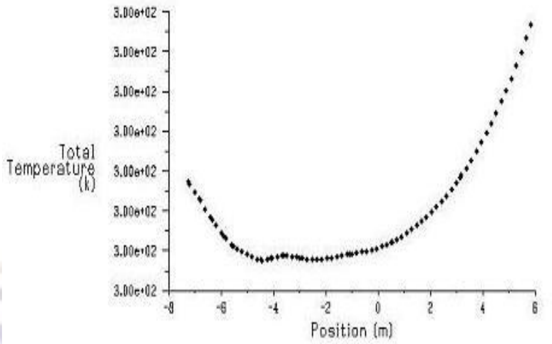

Figure: XY Plot Of Total Temperature With Divergence Angle Of 40 Degrees

The total temperature contour is also similar to the previous version. There is uniformity observed from the inlet to some distance from the throat where it remains a constant whose value is 300 K. After which it increases to 301 K in the centre. The maximum value of 302 K is attained some distance from the wall. There is decrease near the wall. Vertically moving from the centre, it is 301 K up to more than the upper (or) lower half after which it reaches the maximum value of 302 K and then it decreases to the wall where it has a value of 297 K. The variation is similar in the case of 30 nozzles also.

STATIC PRESSURE

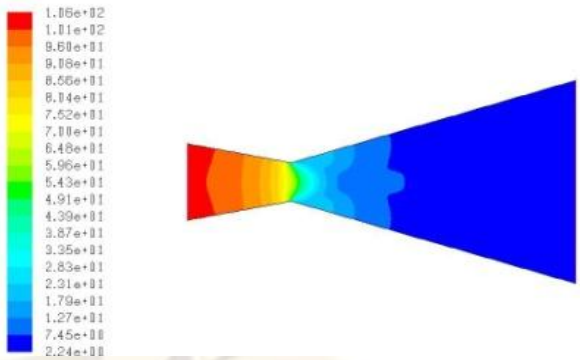

Figure: Static Pressure Contour With Divergence Angle of 40 Degrees

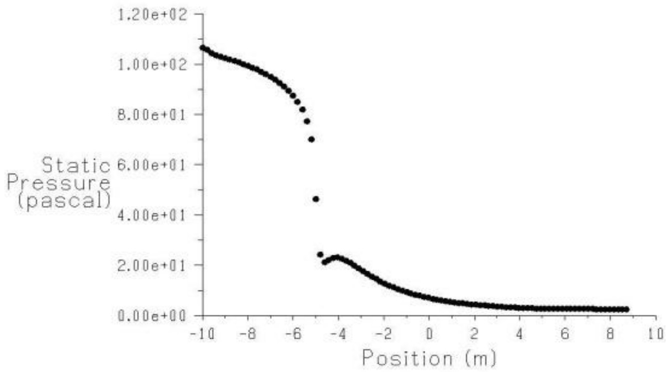

Figure: XY Plot For Static Pressure With Divergence Angle Of 40 Degrees

There is a continuous decrease in the value of static pressure from the inlet to the throat and to the exit. At the inlet it is 106 Pa. It then keeps on decreasing to 75 Pa which is also observed in the case of 30 nozzles. The main difference arises in the exit where there is a deviation in the minimum value in 30 nozzle was 2.24 Pa same as 2.24 Pa for this nozzle. Other than that there is no major difference between the two. The pattern is also similar.

Turbulence intensity

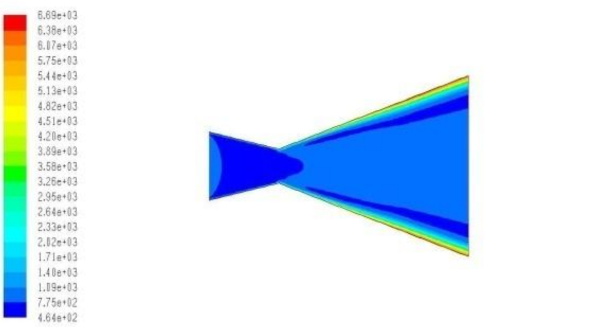

Figure: Turbulence Intensity Contour with Divergence Angle of 40 Degrees

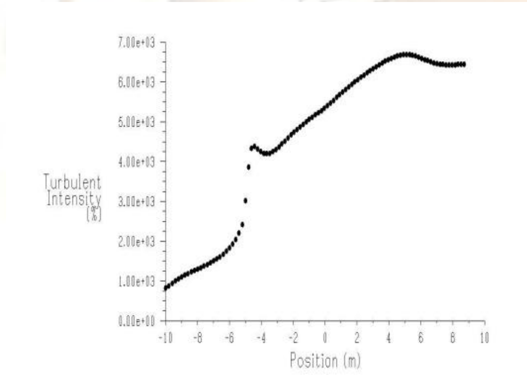

Figure: XY Plot of Turbulence Intensity With Divergence Angle of 40 Degrees

After taking a look at the above Figure and the one for the previous case, it can be said there is a lot of difference in the contour especially in the region after the throat where there is a steep increase when compared to the last case. The exit value has also changed from 1.49e+03 % which was in the previous case to 1.09e+03 % which is in the current one. The turbulent intensity at the inlet is 7.75e+02 % which decreases a little to 7.02e+02 % just after the inlet and remains a constant up to the throat. After the throat there is a sudden increase in the area and hence there is increase in the turbulent intensity. The fluid also does not stabilize here. The maximum turbulent intensity (5.75e+03 %) is obtained near the wall. This is because there is reversal of flow as well as turbulence near the wall.

RESULT TABLE:

Conditions at exit:

CASE	ANGLE	MACH NUMBER	TOTAL TEMPARATURE(K)	STATIC PRESSURE(Pascal)
1	7	2.9	301	3.24
2	20	2.84	300.5	3.86
3	30	3.06	300	2.72
4	40	3.19	301	2.24

The above values are considered at the exit of the nozzle.

Conditions at throat:

CASE	ANGLE	MACH NUMBER	TOTAL TEMPARATURE(K)	STATIC PRESSURE(Pascal)
1	7	1.19	300	65.8
2	20	1.02	300	71
3	30	1.08	300	64.8
4	40	1.12	300.25	59.6

The above values are considered at the throat of the nozzle.

CONCLUSION

The following observations were found in the nozzles with different divergence angles considering default divergence angle as 7 degrees

- In the nozzle with divergence angle of 20 degrees Mach number is 1.15 at throat and at divergence angle of 7 degrees Mach number is 1.19. From Default angle Mach number is increasing up to 2.917 at the nozzle exit while for divergence angle of 20 degrees the Mach number at exit is nearly 2.84.
- At the throat the velocity magnitude is same for all divergence degrees of angle and it is 260 m/s..
- Near the wall, the Mach number is decreasing for all the nozzles. This is due to the viscosity and turbulence in the fluid. For a nozzle of divergence angle of 20 degrees the Mach number at exit is very low compared to other nozzles.
- While when the divergence angle is 30 degrees the Mach number at nozzle exit is 3.06 and but an divergence angle 40 degrees it gives the Mach number at nozzle exit is 3.19 and it is lowest at an divergence angle 20 degrees.
- The turbulence intensity is very high for a divergence angle of 20 degrees at exit.
- For maximum velocity we can go with 30 or 40 degrees of divergence angle conical nozzle.
- The efficiency of the nozzle increases as we increase the divergence angle of the nozzle up to certain extent.

REFERENCES

1. K.M. Pandey, Member IACSIT and A.P. Singh ”CFD Analysis of Conical Nozzle for Mach 3 at Various Angles of Divergence with Fluent Software’’
2. K.M. Pandey, Member IACSIT and A.P. SinghK.M.Pandey, Member, IACSIT and S.K.YadavK.M.Pandey and S.K.Yadav, “CFD Analysis of a Rocket Nozzle with Two Inlets at Mach2.1”, Journal of Environmental Research and Development, Vol 5, No 2, 2010, pp- 308-321.
3. David R. Greatrix, Regression rate estimation for standard-flow hybrid rocket engines, Aerospace Science and Technology 13, 358-363, (2009).
4. P Manna, D Chakraborty “Numerical Simulation of Transverse H2 Combustion in Supersonic Airstream in a Constant Area Duct”, Vol. 86, November 2005, computational combustion Dynamics Division of Defence Research and Development Laboratory, Hyderabad.
5. Yasuhiro Tani “Fundamental study of supersonic combustion in pure air flow with use of shock tunnel” Department of Aeronautics and stronautics, Kyushu University, Japan, Acta Astronautica 57 (2005) 384 – 389.
6. Patankar, S.V. and spalding. D.B. (1974), “ A calculation for the transient and steady state behaviour of shell- and- tube Heat Exchanger”. Heat transfer design and theory sourcebook. Afghan A.A. and Schluner E.U.. Washington. Pp. 155-176.