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Design and numerical analysis on supersonic rocket nozzle

Rocket nozzle is part of a rocket in which the burnt propellant from the combustion chamber can exhaust through the nozzle to get the desire amount of thrust and required Mach number. The nozzle turns the static high pressure high temperature gas to low pressure, low temperature, and high velocity gases. To analyse this we have used CFD. Where CFD is the fluid mechanics which is integral part of the design, this is based on numerical methods and algorithm method. To analyse the fluid flow in supersonic rocket nozzle the CFD analysis software is used. Mainly in this work had focused on the pressure, temperature, velocity and Mach number of the mass flow in nozzle by changing the divergent angle.

The oblique shock is a main conception and the presence of oblique shock which will create the instabilities. And it is visualized that the shock wave is creating in the nozzle at the 5° of divergent angle and it slowly started eliminating from the nozzle after 5° of divergent angle. To overcome this problem some of the trials are made for different divergent angle such as 5°, 10° 11°, 12°, 15°, and 20°. After 12º of divergent angle the flow parameters will start get reducing. At 20º the sudden drop of flow parameter will occur. By considering all the results at different divergent angle, the 11° angle is more efficient and found all the flow parameters such as velocity, temperature, pressure and Mach number of the mass flow are at required condition.

Keywords: CFD; supersonic rocket nozzle; shockwave; divergent angle.

1.0 Introduction

The nozzle has the property to convert the low velocity, high pressure, and high temperature gas in the combustion chamber into high velocity lower pressure and low temperature gases. 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 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. De Lavel's turbine had to run at an impractically high speed.

But for rockets the De Laval nozzle was just what was needed. The many researchers analyzed on the supersonic rocket nozzle one of among them is Karna S. Patel. [1] has investigated about the best suitable divergent angle. The phenomena of oblique shock is visualized and it was found that in between 5° and 10° angle of divergent the oblique shock will eliminate and also intensity of velocity is found to have an increasing trend with increment in divergent angle thereby obtaining an optimum divergent angle which would eliminate instabilities. Similarly the Raghu Ande et al. [3] have investigated that the design of nozzle is a significant aspect for achieving the supreme Mach number and least turbulent intensity. The numerical investigation is done at different divergent angles to find the effect of divergent angle on Mach number and static pressure. The different divergent angles used for examinations are 9°, 12°, 15° and 18°. And predicted that the flow parameters will get reduced after 15°.

B.V.V. Naga sudhakar et al. [2] have focused on the flow parameters of convergent divergent rocket nozzle in which he studied in deep and depth about all these parameters like pressure, temperature and velocity of the mass flow rate at different divergent angle, it is also mentioned some of the important parameters about the nozzle. They have focused mainly design and the numerical part of the supersonic rocket nozzle such as the equations to calculate temperature, pressure and as well on the Mach number. Compared their both the theatrical values to the numerical values which is obtained from the experiment.

By considering all above literatures, the Karna S Patel [1] has not mentioned about the more efficient divergent angle which is suitable for the design of supersonic rocket nozzle. The Raghu Ande et al. [3] have not given the contours for the flow parameters such as velocity and temperature. So in the present work it has been focused on the efficient

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divergent angle for the nozzle which will give the maximum outlet velocity and Mach number. And also focusing on the all flow parameters with their contours at different divergent angles. The divergent angle for supersonic rocket nozzle which we have considered is 5°, 10°, 11°, 12°, 15° and as well as for 20°. The instabilities are created inside the nozzle due to the creation of shock waves which reduce the exit Mach number and also reduces the thrust. This can be completely eliminated by changing the divergent angle of the nozzle. To overcome this problem the trials are made with divergent angles of 5°, 10°, 11°, 12°, 15° and as well as for 20°. During this trial observed that the shock wave is creating inside the nozzle at the divergent angle of 5°. In 10° of divergent angle the shock wave is eliminated. But at the 10° of divergent angle the flow parameters such as velocity, temperature and pressure and Mach number are not at the maximum condition so again the angle of divergent has increased to 11°. In which there is no instabilities and the flow parameters are matching with the requirement. It has also observed that the flow parameters will start reducing after 12°. The trial of 15° of divergent angle is also made to show the decrease in flow parameters. At the angle of 20° the sudden drop of all the parameters will occur. By considering all the results of different divergent angles, the 11° divergent angle of the supersonic rocket nozzle is the more efficient angle.

2.0 Design considaretions and operating parametres

2.1 Design Considerations

To carry out the design of the supersonic rocket nozzle, some of the design aspects are considered. That design considerations are shown in Table 1.

2.2. Operating Parameters

When the design of supersonic rocket nozzle has done then the operating parameters are given as initial boundary conditions. That operating parameters are mentioned in the Table 2.

Table 1: Design consideration

	Design Consideration		
	Parameters	Value	Unit
1	Throat Diameter	34.5	mm
2	Inlet Diameter	166.6	mm
3	Exit Diameter	183	mm

Table 2: Operating parameters

	Operating parameters		
	Parameters	Value	Unit
1	Mach Inlet	0.25	-
2	Gamma	1.41	-
3	Mach at Throat	1	-
4	Mass flow rate	826	Kg/s
5	T0	3400	K
6	P0	4500000	pa

3.0 Meshing approach

Mesh generation also called as a "grid generation" is an important part of CFD analysis. Realistic rendering and high precision simulations depend on the quality of meshing for CFD. The meshing process is the one of the import tasks in order to get the fine and effective type of meshing. The meshing is carried out in ICM CFD with the precision of 0.1. In this work the unstructured type of meshing has done for the supersonic rocket nozzle. The prism type and trigon type meshing elements are used. The meshing has done for the all degree of divergence such as for 5°, 10°, 11º, 15°, and 20°. Fig.1 has given about the mesh in geometry.

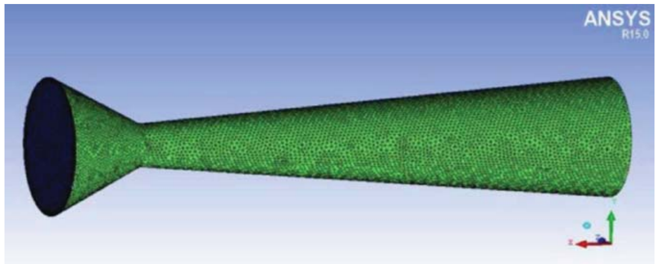

Fig.1. Mesh generation

4.0 CFD post results

We have focused mainly on Mach number, velocity, pressure and the temperature at the different divergent angles such as 5°, 10°,11°,12°,15° and 20°. All results are shown as follows with pressure, velocity and temperature contour.

4.1 Temperature, pressure and velocity contour at 5° divergent angle

The temperature, pressure and velocity contour are shown in Figs.2 to 4. In which the divergent angle is used at 5°. It is observed that the shock wave is creating inside the nozzle. Because of this shock waves the instabilities will occur due to which the flow parameters will get reduced. To overcome this problem the divergent angle is further increased to 10º, 11º, 12º, 15º, and 20º.

The temperature contour is shown in the Fig.2 for the 5º angle of divergent. In which the temperature is so high after the chemical energy turned into the kinetic energy. During the throat section the temperature remains constant and then

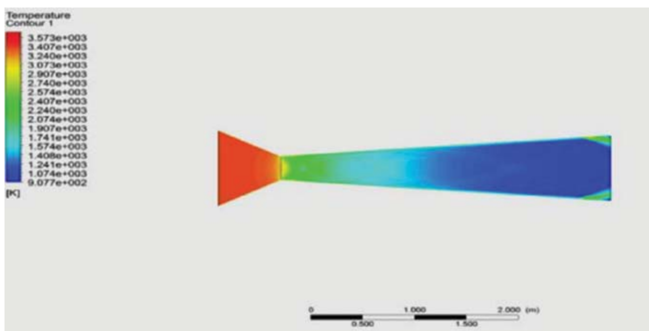

Fig.2: Temperature contour of CD nozzle at 5° divergent angle

gradually increases with increase in velocity. The temperature noticed at the inlet section is 3397K and at the exit section is 1346K

The pressure contour for 5° divergent angle is shown in Fig.3, in which the pressure is high at initial stage then gradually it will start reducing throughout the divergent section of the nozzle. This reduction in pressure intensity is directly proportional to increment in kinetic energy in the form of thrust gained from nozzle at outlet section; this is an essential property for successful launching of rocket. This is observed that the pressure at inlet section is 4.49E+06 Pa and at the exit section of the nozzle is 41285Pa.

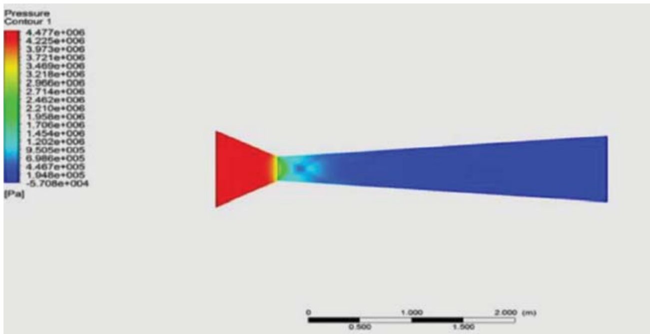

Fig.3: Pressure contour of CD nozzle at 5° divergent angle

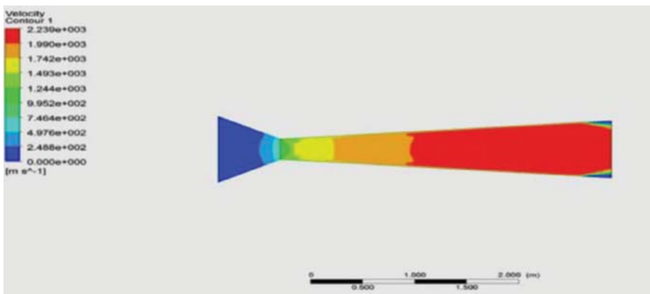

Fig.4: Velocity contour of CD nozzle at 5° divergent angle

In the beginning the velocity is relatively low that is in subsonic condition after the throat section the velocity will get higher and it is at supersonic condition. But because of the instabilities, all the flow parameters are at low condition. The velocity at inlet section is 59.90m/s and at the exit section of the nozzle is 1427.6m/s.

4.2 Temperature, pressure and velocity contour at 10° divergentangle

The temperature, pressure and velocity contour is shown in Figs.5 to 7. In which the divergent angle is used at 10°. The shock wave is eliminating from the exit section of the nozzle. Because of the absence of shock wave there will be no instabilities. This is also observed that the flow parameters are not up to the requirement. So to get more accurate results the divergent angle is increased to 11°, 12°, 15°, and 20°.

The temperature contour is shown for the divergent angle 10° in Fig.5. Where the static temperature almost remains a

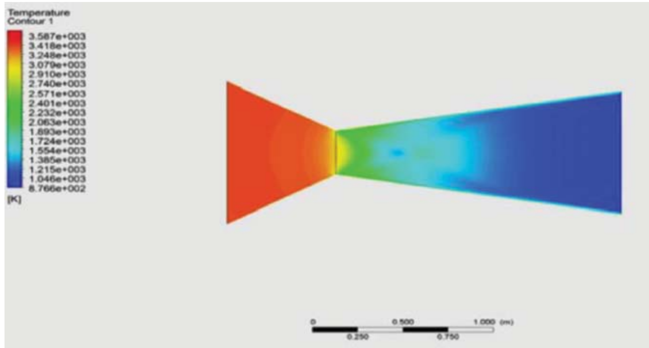

Fig.5: Temperature contour of CD nozzle at 10° divergent angle

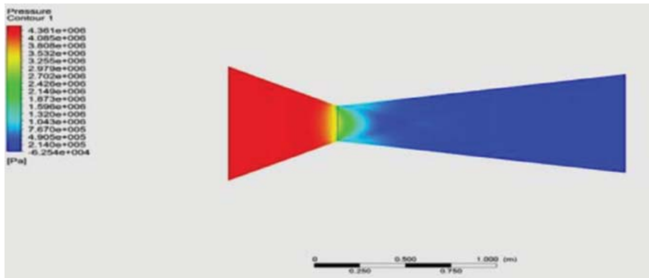

Fig.6. Pressure contour of CD nozzle at 10° divergent angle

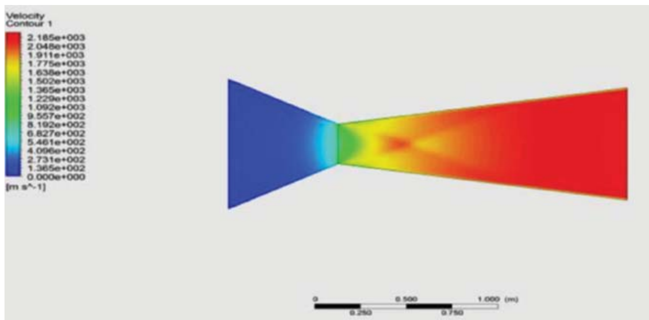

Fig.7: Velocity contour of CD nozzle at 10° divergent angle

constant in the inlet up to the throat. Increase is observed after some distance from the throat towards the exit. The temperature is recorded in inlet section is 3397.4K and at the exit section 1346.5K.

As pressure energy of combustion gases converted into high kinetic energy in order to generate thrust, this increment in kinetic energy also increases collision between molecules and static temperature goes up. The pressure at the inlet section is 4.49E+06 Pa and at the exit section is 53284.2Pa.

The velocity contour is shown for the divergent angle at 10° in Fig.7. In which the velocity at initial condition is low then gradually it will start increasing. It is observed that the velocity at inlet section is 59.9m/s. and at the exit section is 2197.5 m/s.

4.3 Temperature, pressure and velocity contour at 11° divergent angle

The temperature, pressure and velocity contour is shown in Figs.8 to 10 in which the divergent angle is used at 11°.

The shock wave is completely eliminated from the exit section of the nozzle. Because of the absence of shock wave there will be no instabilities. So the velocity, temperature, pressure and Mach number are at the required stage. By considering all the results of different divergent angles the 11° angle of divergent of the nozzle can be considered as the efficient angle for the supersonic rocket nozzle.

It has been observed that the temperature is so high after the chemical energy turned into the kinetic energy. During the throat section the temperature remains constant and then gradually increases with increase in velocity. The temperature is recorded at inlet section for 11° is 3397.5K and at the exit section is 968.2K.

The velocity at the inlet section is 59.9m/s and it is also recorded that the velocity at the exit section is 2197m/s. so it is clearly observed that the velocity is gradually increased.

The pressure is high at initial stage then gradually it will start reducing. It will be constant during the throat section and the pressure contour for 11° as is shown in Fig.10. This is recorded that the pressure at the inlet section is 4.49E+06Pa. and at the exit section 53419.2Pa.

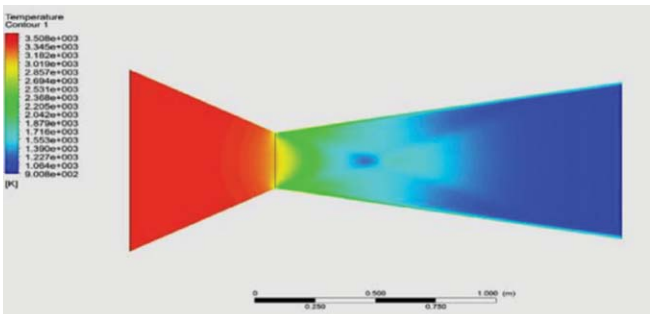

Fig.8: Temperature contour of CD nozzle at 11° divergent angle

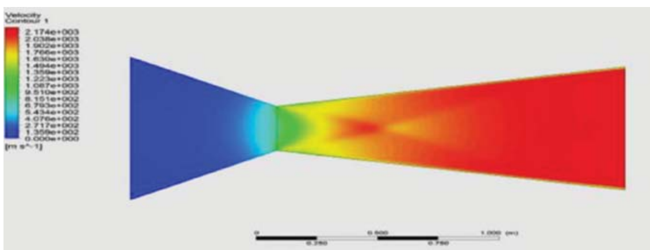

Fig.9: Velocity contour of CD nozzle at 11° divergent angle

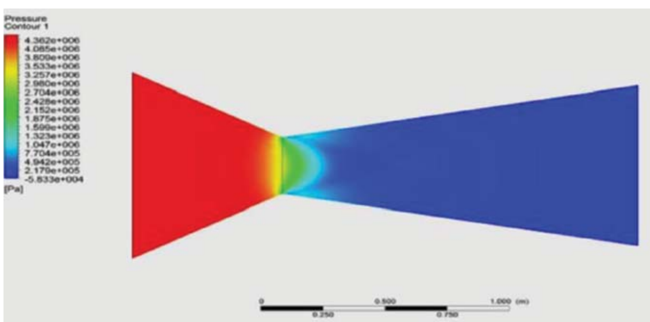

Fig.10: Pressure contour of CD nozzle at 11° divergent angle

4.4 Temperature Pressure and Velocity contour at 12° Divergent angle

The temperature, pressure and velocity contour is shown for the 12° of divergent angle in Figs.11 to 13. The shock wave is completely eliminated from the exit section of the nozzle. Because of the absence of shock wave there will be no instabilities. But this is also observed that the flow parameters will get start reducing because the over expansion of the flow parameters.

It has observed that the temperature is so high after the chemical energy turned into the kinetic energy. During the throat section the temperature remains constant and then gradually increases with increase in velocity. The temperature

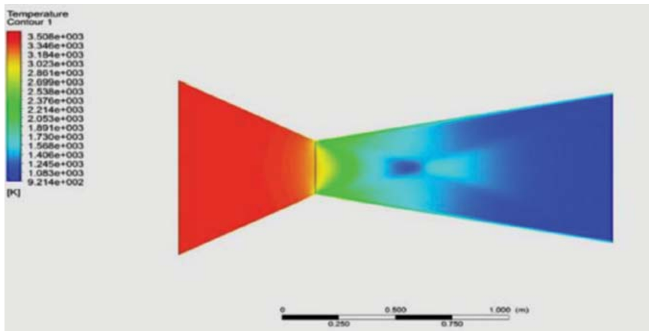

Fig.11: Temperature contour of CD nozzle at 12° divergent angle

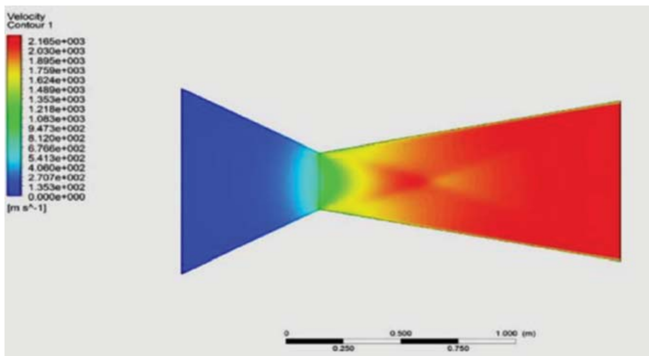

Fig.12: Velocity contour of CD nozzle at 12° divergent angle

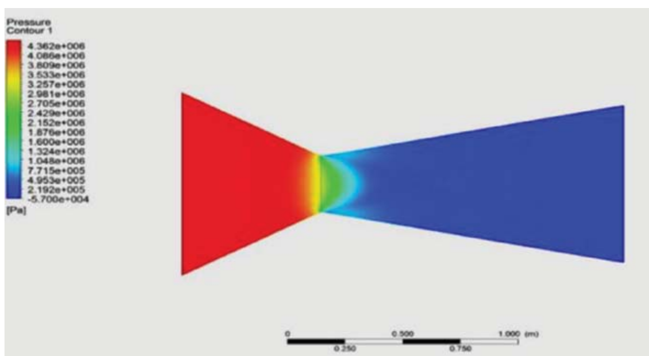

Fig.13. Pressure contour of CD nozzle at 12° divergent angle

at the inlet section is 3397K and it is also recorded that the temperature at the exit section is 977K.

The velocity contour for the 12° is shown in the Fig.12 in which the velocity at the inlet section is 59.9m/s. and at the exit section 2190.5m/s by comparing this value with 11° of divergent angle; it is clearly visible that the velocity is decreasing.

Initially the pressure is at a peak condition gradually it will start decreasing. The pressure contour is shown in the Fig.13, for 12° of divergent angle. The pressure at the inlet section is 4.49E+06 Pa. and the exit section is 52873Pa.

4.5 Temperature pressure and velocity contour at 15° divergentangle

The temperature, pressure and velocity contour is shown in Figs.14 to 16, in which the divergent angle is used at 15°. It has observed that the temperature is so high after the chemical energy turned into the kinetic energy. During the throat section the temperature remains constant and then gradually increases with increase in velocity. The pressure is high at initial stage then gradually it will start reducing. The divergent angle is 15° so the shock wave is completely eliminated from the exit section of the nozzle. Because of the absence of shock wave there will be no instabilities. This is also observed that the flow parameters will get start reducing because of over expansion of the flow parameters.

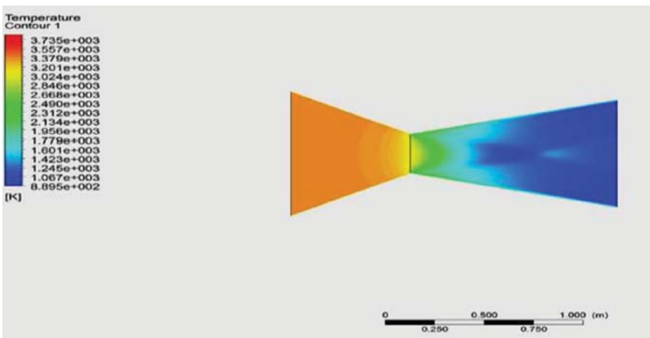

Fig.14. Temperature contour of CD nozzle at 15° divergent angle

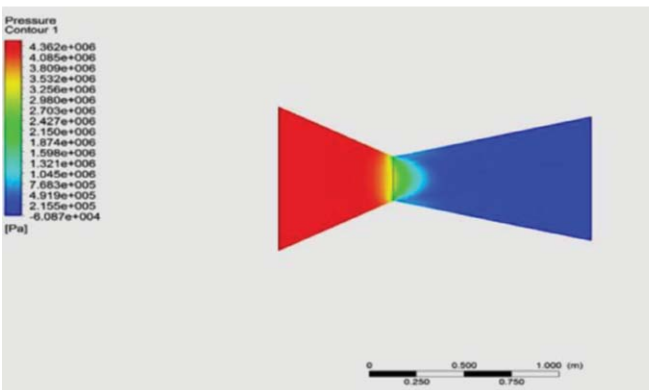

Fig.15: Pressure contour of CD nozzle at 15° divergent angle

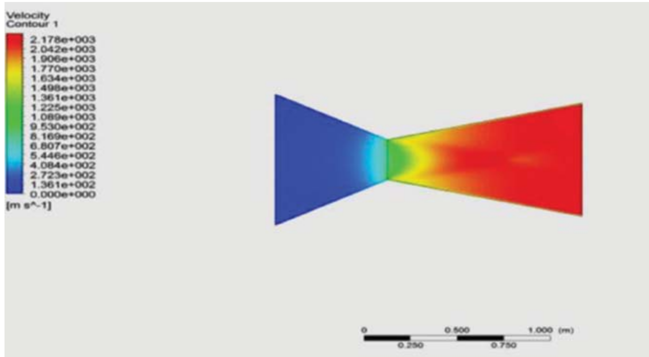

Fig.16: Velocity contour of CD nozzle at 15° divergent angle

The temperature contour is shown in the Fig.14, for the divergent angle at 15°, in which the temperature at inlet section is 3397.5K and at the exit section of the nozzle is 990.3K.

The pressure contour is shown in the Fig.15. For the divergent angle at 15° in which the pressure at inlet section is 4.49E+06Pa and at the exit section of the nozzle is 52258Pa.

The velocity contour is shown in the Fig.16. For the divergent angle at 15°, in which the velocity at inlet is 59.3m/s and at the exit section of the nozzle is 2186.5m/s.

4.6 Temperature pressure and velocity contour at 20° divergentangle

The temperature, pressure and velocity contour is shown in Figs.17 to 19, in which the divergent angle is used at 20°. It has observed that the temperature is so high in the beginning stage and then started decreasing. The pressure is high at beginning and reduces at the exit with increase in the velocity. This has observed that the sudden drop of all the flow parameters will occur.

Initially in the inlet section the temperature is at high and it will remain constant through the throat, then the temperature will start decreasing. This is noted that the temperature at inlet section is 3397.5K and at the exit section is 1102.8K.

The pressure contour is shown in the Fig.18. For the divergent angle at 20°, in which the pressure at inlet section is 4.49E+06Pa and at the exit section of the nozzle is 14692Pa.

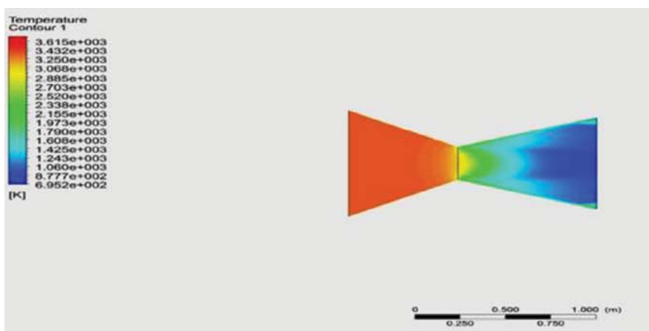

Fig.17: Temperature contour of CD nozzle at 20° divergent angle

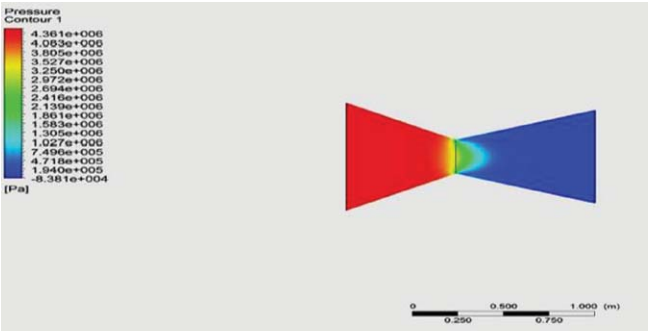

Fig.18. Pressure contour of CD nozzle at 20° divergent angle

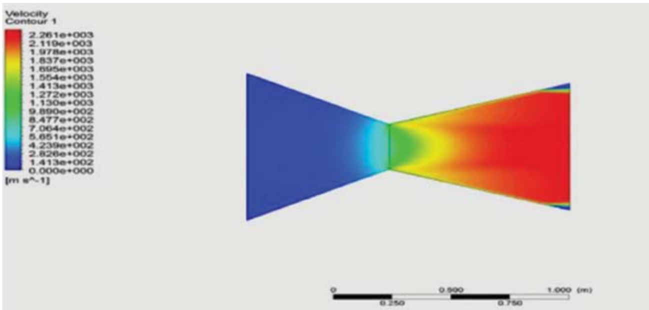

Fig.19. Velocity contour of CD nozzle at 20° divergent angle

The velocity at the exit section of divergent angle at 20º, it will be at very low condition because of the over expansion of all flow parameters. It is noticed that at the divergent angle at 20º. The sudden drop of all the flow parameters will occur. The velocity at the inlet section is 59.64m/s and at the exit section is 1889.6m/s, has been noted.

4.7 Exit section values (Table 3)

Table 3: Exit section values

Angle	5o	10º	11º	12º	15º	20º
Exit velocity (m/S)	1427	2191	2197	2190	2186	1889
Exit temperature (K)	1346	972	968	977	990	1102
Exit pressure (Pa)	41285	53926	53419	52873	52258	14692
Exit mach number	1.94	3.5	3.52	3.49	3.46	2.83

5.0 Conclussion

The results were found after conducting this investigation and tabulated in the Table 3. The trials are made on the divergent angle 5°, 10°, 11°, 12°, 15° and as well as on 20°. During the trials it is observed that oblique shock is formed during flow through the nozzle, when the divergent angle is 5°. It is also observed that the shock is completely eliminated from the nozzle when divergent angle increases to 10° and to get more accurate results the convergence have made on 11°, 12°, 15° and 20°. All the flow parameters were considered such as pressure, temperature, velocity and as well as Mach number. We have observed that at 11° divergent angle the all flow parameters are matching as per our requirements. After the 11º of divergent angle all the flow parameters will start reducing. It also noticed that at the 20° divergent angle the sudden drop of all the flow parameters will occur. By considering all these results at different divergent angles 11º can be considered as a good design for the supersonic rocket nozzle.

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