International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395-0056
Volume: 08 Issue: 08 | Aug 2021 www.irjet.net p-ISSN: 2395-0072

Modelling and Analysis of a Convergent – Divergent Nozzle

Fareen Nizami[1], Dr. Basawaraj[2], Sanjeev G Palekar[3], Prashant Channaveere[4]

[1]P.G. Student, Department of Aerospace Propulsion Technology, Visvesvaraya Technological University-Centre for Post Graduate Studies, Bengaluru Region, VIAT, Muddenahalli, Chickballapur, Karnataka, India
[2]Associate Professor& Chairman, Department of Aerospace Propulsion Technology, Visvesvaraya Technological University-Centre for Post Graduate Studies, Bengaluru Region, VIAT, Muddenahalli, Chickballapur, Karnataka, India
[3]Assistant Professor, Department of Aerospace Propulsion Technology, Visvesvaraya Technological University-Centre for Post Graduate Studies, Bengaluru Region, VIAT, Muddenahalli, Chickballapur, Karnataka, India
[4]Assistant Professor, Department of Aeronautical Engineering, East West College of Engineering, Yelahanka New Town, Bangalore, Karnataka, India.

Abstract - *Nozzle is a part of the propulsion system which is used to accelerate the hot gases flowing through it. The nozzle geometry is highly important because it directly affect the overall performance of propulsion system. Also, design of nozzle is an important aspect for achieving the maximum Mach number or supersonic speed. To achieve supersonic speed a type of nozzle called Convergent - Divergent nozzle or otherwise known as the de Laval nozzle or CD nozzle is used which converts the high temperature, high pressure, and low velocity gas into high velocity and low pressure gas at the exit. The main aim of this work is to model Convergent – Divergent nozzle and analyse the variation in flow parameters that are static pressure, velocity, static temperature and Mach number by modifying the nozzle divergent angle, keeping same throat and inlet diameter and by using the optimum convergent angle of 28.5°. Analysis is carried out for divergent angles 5°, 10°, 15° and 20° using computational fluid dynamics software(CFD). CFD results were compared with the theoretical results. Variation in flow parameters at the nozzle outlet is studied so as to find the optimum divergent angle for the optimum convergent angle. By considering the results of all the divergent angles 20° gave maximum Mach number that will lead to improve performance of the nozzle and thereby the power and efficiency of a propulsion system.*

Key Words: Convergent – Divergent nozzle, Divergent angle, Convergent angle, CFD analysis, ANSYS Fluent

1.INTRODUCTION

Nozzle is a very essential component of the propulsion system whose function is to accelerate the hot gases flowing through it. It controls the rate of flow, direction and pressure. It also converts pressure energy into kinetic energy. The performance of nozzle greatly affects the efficiency of propulsion system. Generally, there are different types of nozzles. Convergent – Divergent nozzle are among the one which are in great demand in order to achieve supersonic speeds, required in various fields of engineering. The Convergent-Divergent or CD nozzle is used in rocket engines, supersonic jet engines and in some steam turbines. It is also known as the de-Laval nozzle.

The gas passing through a CD nozzle is isentropic and adiabatic in nature. From Figure 1 we can see that first the flow is subsonic. This happens at the convergent section of the nozzle followed by the throat where the area is the smallest and the Mach number is 1. Here the flow becomes sonic in nature. This phenomenon is called "Choked Flow". Next as the gas passes through the divergent section, the nozzle cross-sectional area increases. The gas undergoes expansion and reaches supersonic velocity. The performance of this nozzle depends upon the flow parameters which are affected by the geometry of the nozzle.

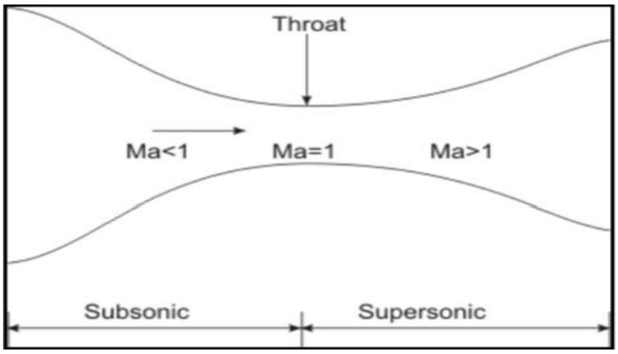

Fig -1: Convergent-Divergent nozzle

Many researchers have worked to obtain an optimum geometry of the Convergent – Divergent nozzle. Karna S. Patel [1] has modelled different geometries of a Convergent - Divergent nozzle with 5°, 10° and 15° divergent angle have undergone analysis using computational fluid dynamics software (CFD), in which 15° geometry gave the efficient results. Biju Kuttan P et al., [2] have carried out work to analyse the variations of flow parameters like the static pressure, Mach number, turbulent intensity by taking 4°, 7°, 10°, 13° and 15° as divergent angles were 15° was considered the good nozzle design. I. Mir et al., [3] have carried out analysis on different geometrical configurations of a Convergent - Divergent nozzle by varying convergent section length from 602 mm to 655 mm and convergent angle from 28° to 30°, the geometry with 640 mm convergent length and 28.5° convergent angle was giving the maximum thrust. B.V.V. Naga Sudhakar et al., [4] have conducted analysis to study the flow parameters such as pressure, temperature and velocity at each section of the nozzle for divergent angle of 11°. MD. Safayet Hossain et al., [5] have carried out comparative flow analysis for 10° and 20° divergent angles by keeping constant the inlet area, throat area and nozzle length, in which 20° gave the efficient result. The main aim of this work is to obtain an optimized geometry of the Convergent – Divergent nozzle by observing the flow parameters. Different 3D models of Convergent – Divergent nozzle with divergent angle 5°, 10°, 15°, and 20° are created using Ansys Workbench. Create models are then meshed in Ansys Workbench itself. CFD analysis is carried on these meshed models using Ansys Fluent, to obtain the flow parameters that are static pressure, velocity, static temperature and Mach number. Parameshwar Banakar et al., [6] have carried out analysis using 45^0 sector model of diffuser mixer with struts and without struts by considering the periodicity of geometry. An unstructured grid is generated and by using Ansys Fluent Software simulation has been done. The analysis has been carried out with total pressure, velocity components and total temperature at inlet boundary conditions and a mass flow rate at the outlet.

2. THEORTICAL FORMULATION OF NOZZLE

To obtain the flow parameters theoretically the following equations are used:

$$\frac{T_0}{T} = [1 + \frac{1}{2}(\gamma - 1)M^2]$$

$$\frac{P_0}{P} = [1 + \frac{1}{2}(\gamma - 1)M^2]^{\frac{\gamma}{(\gamma-1)}}$$

$$V = M\sqrt{\gamma RT}$$

Where,

T_0 - Temperature at a point where the velocity = 0, in K

T - Temperature at a particular location in the nozzle, in K

M = Mach number at a particular location in the nozzle

P_0 = Pressure at a point where the velocity = 0, in Pa

P = Pressure at a particular location in the nozzle, in Pa

γ = Ratio of specific heat constant for air

R = Gas constant, in J/kg –K

V = Velocity at a particular location in the nozzle, in m/s

3. MODELLING

The 3D nozzle was modelled in ANSYS workbench software. The standard dimensions for the nozzle were obtained by referring journal from Research Gate. The dimensions are tabulated in Table 1. For each simulation the divergent angle is modified.

Table -1: Nozzle Dimensions

Parameter	Dimension
Inlet diameter	1000 mm
Outlet diameter	861 mm
Throat diameter	304 mm
Converging length	640 mm
Convergent angle	28.5°
Divergent angle	5°, 10°, 15° and 20°

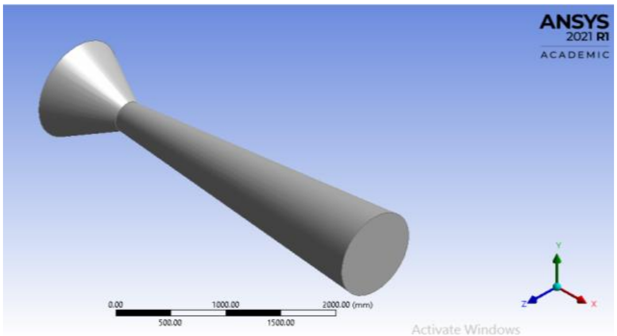

Fig -2: 3D modelled nozzle with 5° divergent angle

4. MESHING

After the modelling is done, the nozzle is meshed in ANSYS workbench itself. The meshed model for divergent angle 5° is shown in Figure 3.

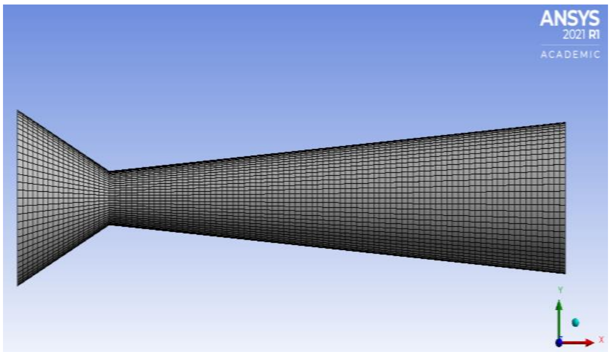

Fig -3: Nozzle after meshing

5. SETUP AND SOLUTION

The meshed 3D models will be assigned with double precision settings, density based solver type and absolute velocity formulation in ANSYS Fluent. Also, the various input parameters and boundary conditions will be given to the models which are tabulated in Table 2.

Table -2: CFD Input parameters and Boundary conditions

Parameter	Dimension
Viscous model	SST k-omega
Material	air
Viscosity	1.7894e-5 kg/m-s
Inlet temperature	3400K

Inlet pressure	45 bar
Number of iterations	1000

The simulation is run for 1000 number of iterations and the criteria of convergence given are tabulated in Table 3.

Table -3: Criteria of Convergence

Residuals	Absolute Criteria
continuity	0.001
x-Velocity	0.001
y-Velocity	0.001
z-Velocity	0.001
k	0.001
omega	0.001
energy	0.001

6. RESULTS AND DISCUSSIONS

By analysing the different cases of Convergent - Divergent nozzle in Ansys Fluent, different contours and plots are obtained for flow parameters such static pressure, velocity, static temperature and Mach number.

__Case 1:__ Convergent – Divergent nozzle for divergent angle = 5°

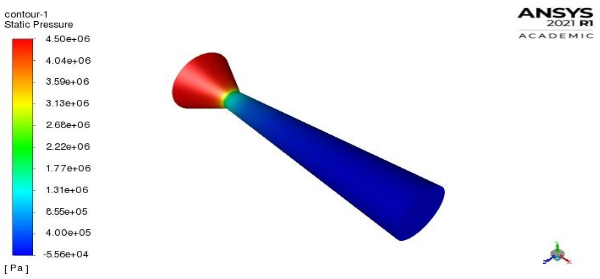

Fig -4: Static pressure contour with 5° divergent angle

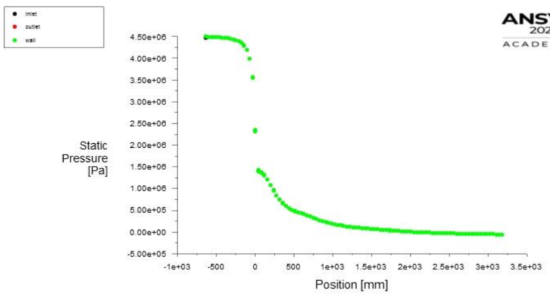

Fig -5: Static pressure VS Position plot for 5° divergent angle

Fig 4 and 5 shows the static pressure variation along the length of nozzle, whose value is maximum at the inlet which is 4.50e+06 Pa and gradually decreases towards the outlet of the nozzle where it is minimum i.e. -5.56e+04 Pa, as the pressure energy of the fluid gets converted to kinetic energy.

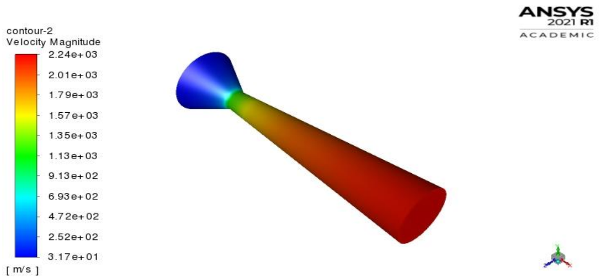

Fig -6: Velocity magnitude contour for 5° divergent angle

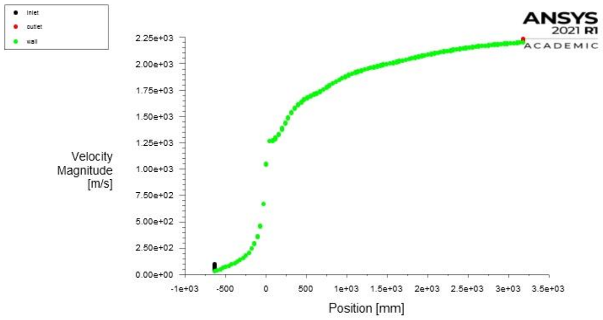

Fig -7: Velocity magnitude VS Position plot for 5° divergent angle

Fig 6 and 7 shows the velocity magnitude variation along the length of nozzle, whose value is less at inlet i.e. 3.17e+01 m/s and more at outlet i.e. 2.24e+03 m/s. As it is known that the nozzle increases the velocity by decreasing the static pressure i.e. changing pressure energy to kinetic energy.

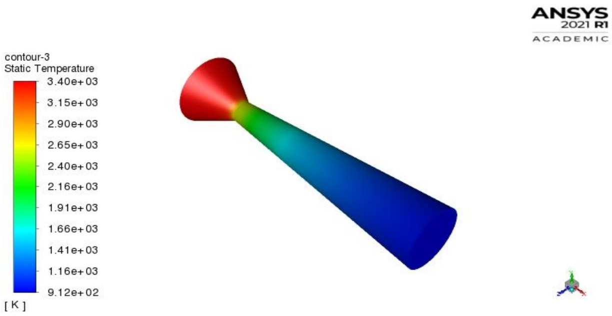

Fig -8: Static temperature contour for 5° divergent angle

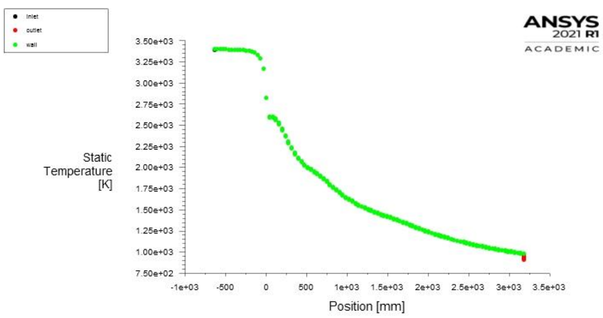

Fig -9: Static temperature VS Position plot for 5° divergent angle

Fig 8 and 9 shows the static temperature variation along the length of nozzle, whose value is maximum at the inlet which is 3.4e+03 K and gradually decreases towards the outlet of the nozzle where it is minimum i.e. 9.12e+02 K, as the exhaust gases gets expanded at outlet.

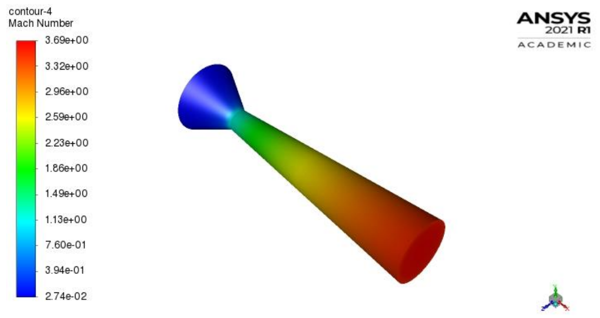

Fig -10: Mach number contour for 5° divergent angle

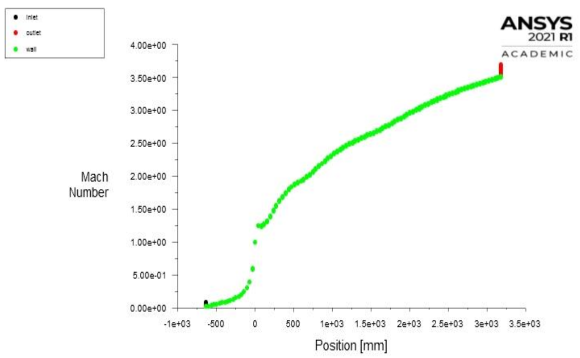

Fig -11: Mach number VS Position plot for 5° divergent angle

Fig 10 and 11 shows the Mach number variation along the length of nozzle, whose value is less at inlet i.e. 2.74e-2 and more at outlet i.e. 3.69. As it is known that nozzle increases the velocity and hence the Mach number increases.

__Case 2:__ Convergent – Divergent nozzle with divergent angle = 10°

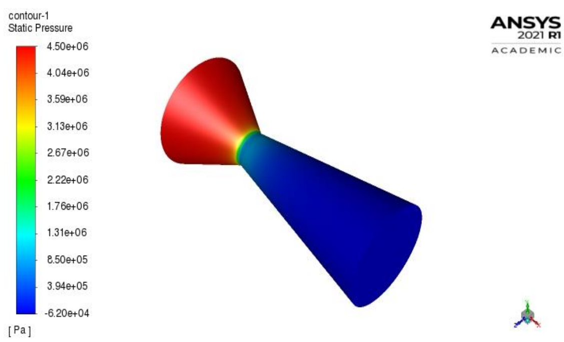

Fig -12: Static pressure contour for 10° divergent angle

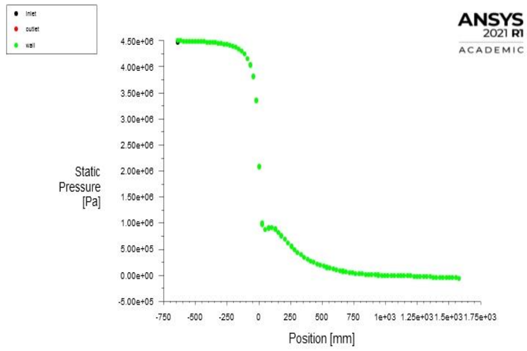

Fig -13: Static pressure VS Position plot for 10° divergent angle

Fig 12 and 13 shows the static pressure variation along the length of nozzle, whose value is maximum at the inlet which is 4.50e+06 Pa and gradually decreases towards the outlet of the nozzle where it is minimum i.e. -6.20e+04 Pa, as the pressure energy of the fluid gets converted to kinetic energy.

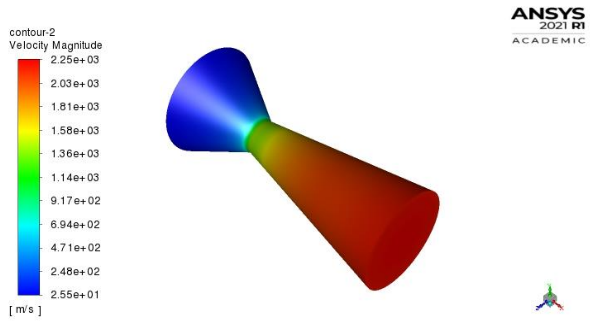

Fig -14: Velocity magnitude contour for 10° divergent angle

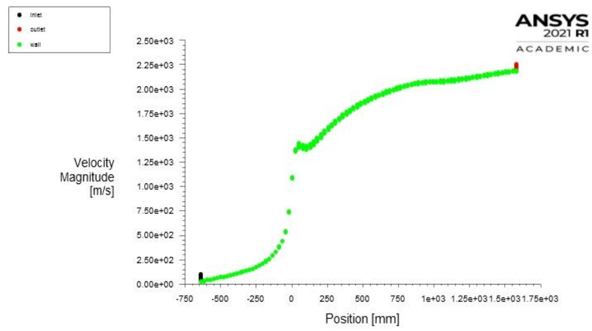

Fig -15: Velocity magnitude VS Position plot for 10° divergent angle

Fig 14 and 15 shows the velocity magnitude variation along the length of nozzle whose value is less at inlet i.e. 2.55e+01 m/s and more at outlet i.e. 2.25e+03 m/s. As it is known that the nozzle increases the velocity by decreasing the static pressure i.e. changing pressure energy to kinetic energy.

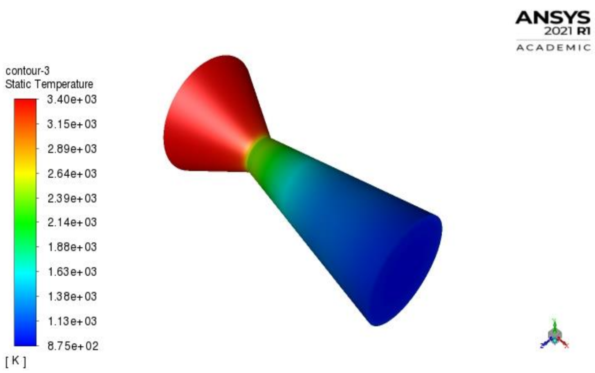

Fig -16: Static temperature contour for 10° divergent angle

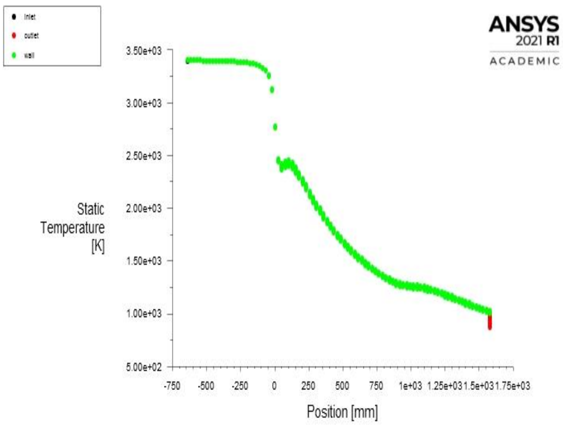

Fig -17: Static temperature VS Position plot for 10° divergent angle

Fig 16 and 17 shows the static temperature variation along the length of nozzle, whose value is maximum at the inlet which is 3.4e+03 K and gradually decreases towards the outlet of the nozzle where it is minimum i.e. 8.75e+02 K, as the exhaust gases gets expanded at outlet.

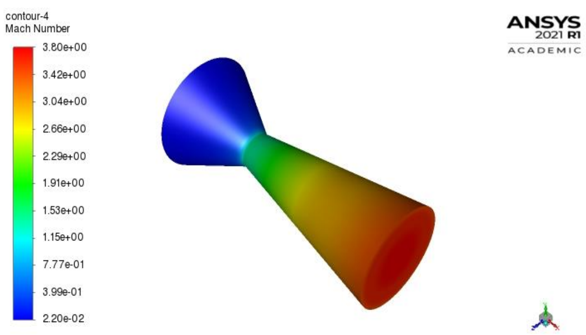

Fig -18: Mach number contour for 10° divergent angle

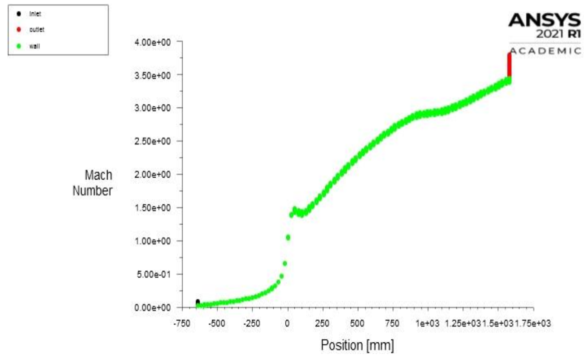

Fig -19: Mach number VS Position plot for 10° divergent angle

Fig 18 and 19 shows the Mach number variation along the length of nozzle, whose value is less at inlet i.e. 2.20e-2 and more at outlet i.e. 3.80. As it is known that nozzle increases the velocity and hence the Mach number increases.

Case 3: Convergent – Divergent nozzle with divergent angle = 15°

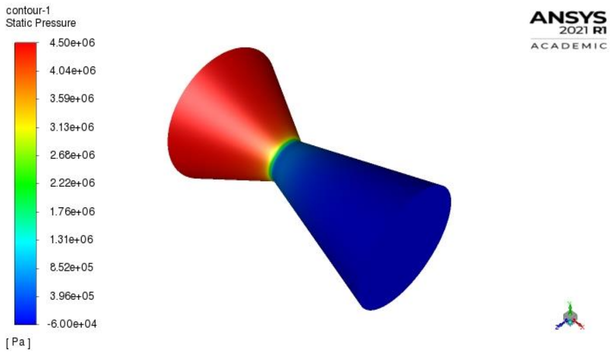

Fig -20: Static pressure contour for 15° divergent angle

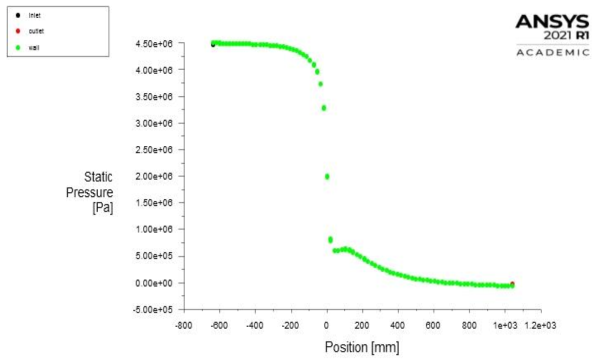

Fig -21: Static pressure VS Position plot for 15° divergent angle

Fig 20 and 21 shows the static pressure variation along the length of nozzle, whose value is maximum at the inlet which is 4.50e+06 Pa and gradually decreases towards the outlet of the nozzle where it is minimum i.e. -6e+04 Pa, as the pressure energy of the fluid gets converted to kinetic energy.

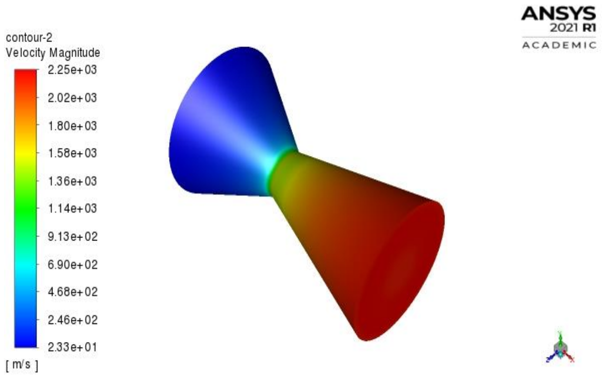

Fig -22: Velocity magnitude contour for 15° divergent angle

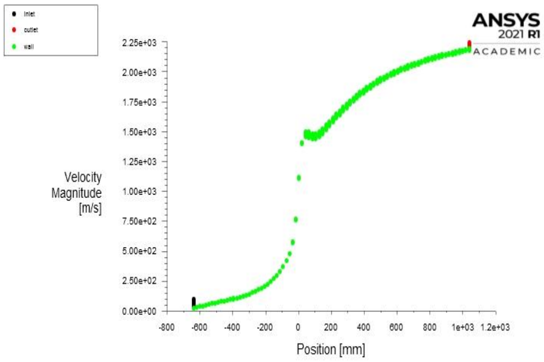

Fig -23: Velocity magnitude VS Position plot for 15° divergent angle

Fig 22 and 23 shows the velocity magnitude variation along the length of nozzle, whose value is less at inlet i.e. 2.33e+01 m/s and more at outlet i.e. 2.25e+03 m/s. As it is known that the nozzle increases the velocity by decreasing the static pressure i.e. changing pressure energy to kinetic energy.

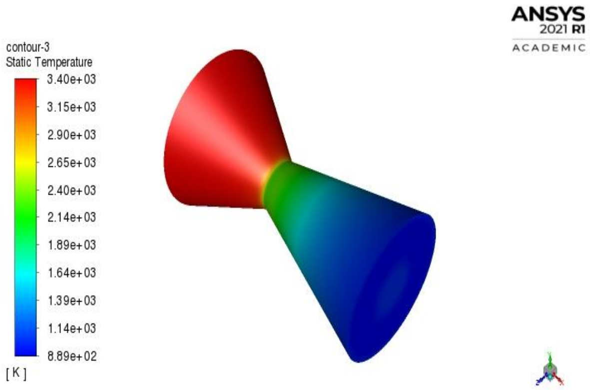

Fig -24: Static temperature contour for 15° divergent angle

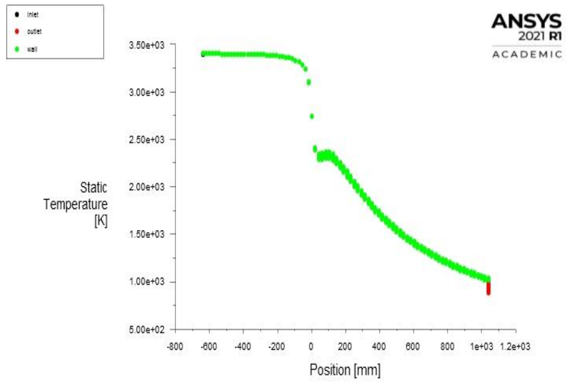

Fig -25: Static temperature VS Position plot for 15° divergent angle

Fig 24 and 25 shows the static temperature variation along the length of nozzle, whose value is maximum at the inlet which is 3.4e+03 K and gradually decreases towards the outlet of the nozzle where it is minimum i.e. 8.89e+02 K, as the exhaust gases gets expanded at outlet.

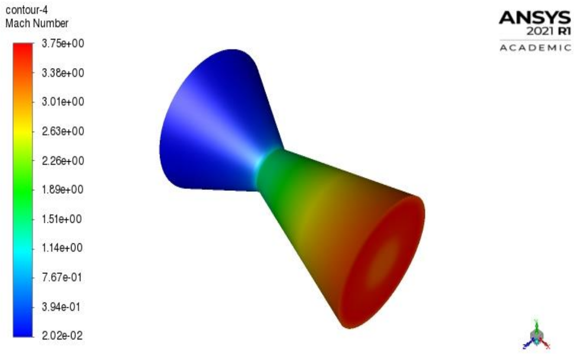

Fig -26: Mach number contour for 15° divergent angle

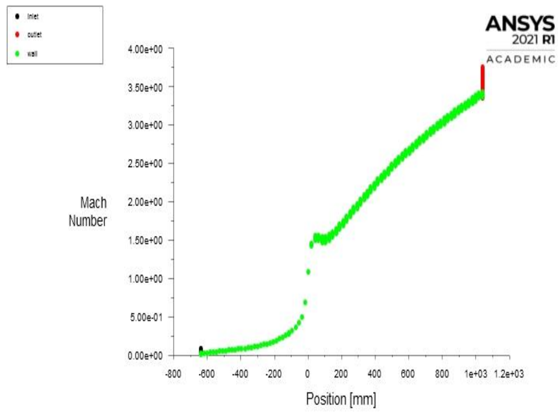

Fig -27: Mach number VS Position plot for 15° divergent angle

Fig 26 and 27 shows the Mach number variation along the length of nozzle, whose value is less at inlet i.e. 2.02e-2 and more at outlet i.e. 3.75. As it is known that nozzle increases the velocity and hence the Mach number increases.

Case 4: Convergent – Divergent nozzle with divergent angle = 20°

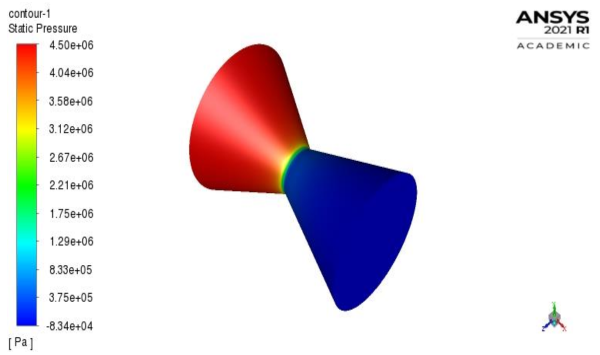

Fig -28: Static pressure contour for 20° divergent angle

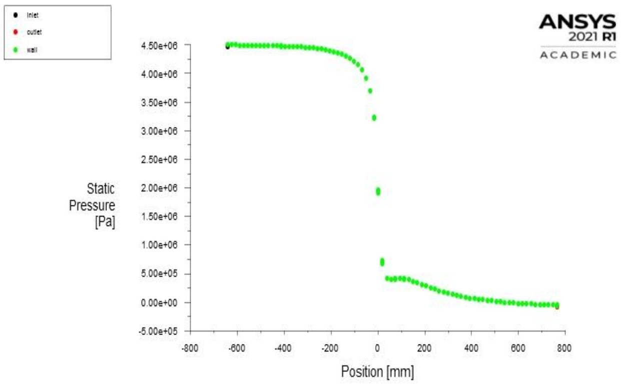

Fig -29: Static pressure VS Position plot for 20° divergent angle

Fig 28 and 29 shows the static pressure variation along the length of nozzle, whose value is maximum at the inlet which is 4.50e+06 Pa and gradually decreases towards the outlet of the nozzle where it is minimum i.e. -8.34e+04 Pa, as the pressure energy of the fluid gets converted to kinetic energy.

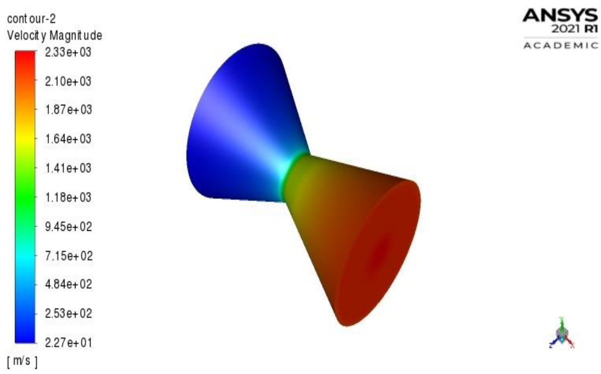

Fig -30: Velocity magnitude contour for 20° divergent angle

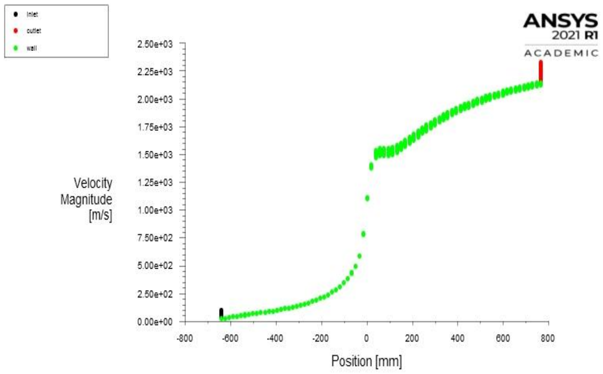

Fig -31: Velocity magnitude VS Position plot for 20° divergent angle

Fig 30 and 31 shows the velocity magnitude variation along the length of nozzle, whose value is less at inlet i.e. 2.27e+01 m/s and more at outlet i.e. 2.33e+03 m/s. As it is known that the nozzle increases the velocity by decreasing the static pressure i.e. changing pressure energy to kinetic energy.

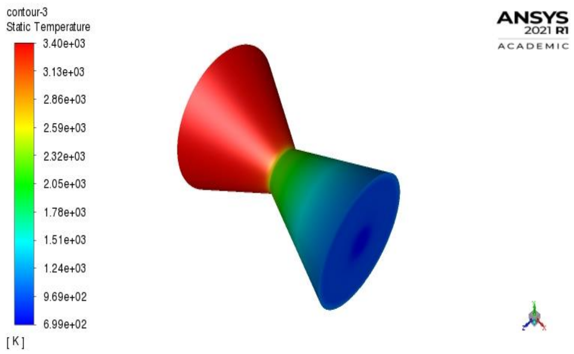

Fig -32: Static temperature contour for 20° divergent angle

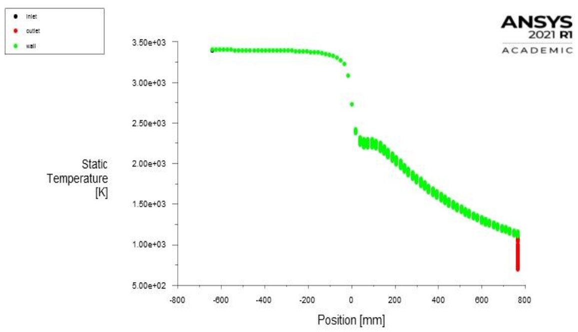

Fig -33: Static temperature VS Position plot for 20° divergent angle

Fig 32 and 33 shows the static temperature variation along the length of nozzle, whose value is maximum at the inlet which is 3.4e+03 K and gradually decreases towards the outlet of the nozzle where it is minimum i.e. 6.99e+02 K, as the exhaust gases gets expanded at outlet.

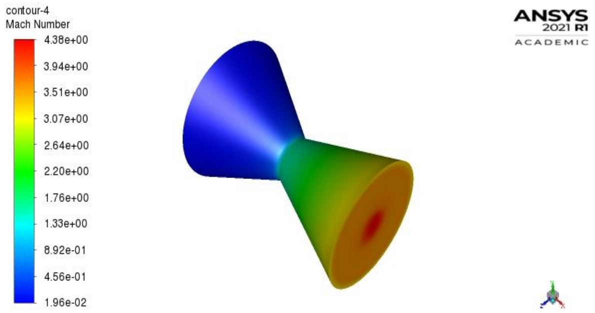

Fig -34: Mach number contour for 20° divergent angle

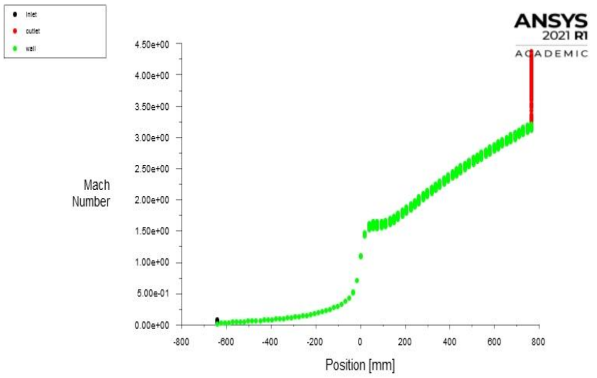

Fig -35: Mach number VS Position plot for 20° divergent angle

Fig 34 and 35 shows the Mach number variation along the length of nozzle, whose value is less at inlet i.e. 1.96e-2 and more at outlet i.e. 4.38. As it is known that nozzle increases the velocity and hence the Mach number increases.

The values of the flow parameters at the exit section obtained from the CFD simulation and theoretical calculations for various divergent angles of the nozzle are presented in below Table 4 and Table 5 respectively.

Table -4: Flow parameters values at nozzle exit obtained by CFD simulation

Angle	5°	10°	15°	20°
Static Pressure in Pa	-55600	-62000	-60000	-83400
Velocity Magnitude in m/s	2240	2250	2250	2330
Static Temperature in K	912	875	889	699
Mach Number	3.69	3.80	3.75	4.38

Table -5: Flow parameters values at nozzle exit obtained by theoretical calculation

Static Pressure in Pa	Velocity Magnitude in m/s	Static Temperature in K	Mach number
40581	2104.8911	850.833	3.6

7. CONCLUSION

By comparing the results of different divergent angles, Convergent – Divergent nozzle with divergent angle 20° is giving the efficient flow parameters and maximum Mach number compared to all other geometries. Hence, the Convergent – Divergent nozzle with the divergent angle 20° is considered to be the optimized geometry which can lead to improve the performance of nozzle and in turn the performance of the propulsion system.

REFERENCES

[1] Karna S. Patel, "Flow Analysis and Optimization of Supersonic Rocket Engine Nozzle at Various Divergent Angle using Computational Fluid Dynamics (CFD)", IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE), Volume 11, Issue 6, Nov-Dec. 2014, pp. 01-10.

[2] Biju Kuttan P and M Sajesh, "Optimization of Divergent Angle of a Rocket Engine Nozzle Using Computational Fluid Dynamics", The International Journal of Engineering and Science (IJES), Volume 2, Issue 2, 2013, pp. 196-207.

[3] I. Mir, S. Samo, T. Hussain, I. Ali, H. A. K. Durani, "Influence of Convergent Section Length and Angle on Performance of Supersonic Nozzle", Sindh University. Research. Journal. (Science. Series.), Volume 49 (004), 2017, pp. 727-732.

[4] B.V.V. Naga Sudhakar, B Purna Chandra Sekhar, P Narendra Mohan, MD Touseef Ahmad, "Modeling and simulation of Convergent-Divergent Nozzle Using Computational Fluid Dynamics", International Research Journal of Engineering and Technology (IRJET), Volume 03, Issue 08, Aug. 2016, pp. 346 - 350.

[5] MD. Safayet Hossain, Muhammad Ferdous Raiyan, Nahed Hassan Jony, "Comparative Study of Supersonic Nozzles", IJRET: International Journal of Research in Engineering and Technology, Volume 03, Issue 10, Oct. 2014, pp. 351 – 357.

[6] Parmeshwar Banakar, Dr. Basawaraj, "Computational Analysis of flow in after Burner Diffuser Mixer Having Different shapes of Struts", International Journal of Engineering Research(IJEOR), Volume 3, Issue 6, 2015, pp. 225-229.

BIOGRAPHIES

Ms. Fareen Nizami
Secured Rank 3 in VTU 18th Convocation 2019, Presently, P.G. Student, Department of Aerospace Propulsion Technology, VTU-CPGS Bengaluru Region, VIAT, Muddenahalli, Chickballapur, Karnataka, India.

Dr. Basawaraj
Associate Professor & Chairman, Department of Aerospace Propulsion Technology, VTU-CPGS Bengaluru Region, VIAT, Muddenahalli, Chickballapur, Karnataka, India.

Mr. Sanjeev G Palekar
Assistant Professor, Department of Aerospace Propulsion Technology, VTU-CPGS, Bengaluru Region, VIAT, Muddenahalli, Chickballapur, Karnataka, India.

Mr. Prashant Channaveere
Assistant Professor, Department of Aeronautical Engineering, East West College of Engineering, Yelahanka New Town, Bangalore, Karnataka, India.