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Design and flow analysis of Convergent Divergent nozzle using CFD

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Abstract:* Nozzle is a device which is used to give the direction to the gases coming out of the combustion chamber. Nozzle is a tube which has a capacity to convert the thermo-chemical 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. A convergent divergent nozzle is used if the nozzle pressure ratio is high. High performance engines in supersonic aircrafts generally incorporate some form of a convergent-divergent nozzle. In this work an analysis is carried using software Solid Works Module for designing of the nozzle and ANSYS Fluent 15.0 for analyzing the flows in the nozzle. This work contains analysis over a convergent divergent rocket nozzle which is performed by varying the divergent angle of the convergent divergent nozzle and the contours of the pressure, velocity, temperature, density and Mach number are determined. The angle of divergence for the divergent portion is varied and its corresponding parameters are studied and convergence of flow is obtained at 554 iterations using Computational Fluid Dynamics (CFD).From the solutions obtained it is observed that the optimized angle for the divergence in the Convergent Divergent Nozzle is 14^o – 15^o to obtain maximum velocity and the higher propulsions for the rocket engines can be achieved with this angle.

Keywords: Convergent Divergent nozzle, SolidWorks, ANSYS FLUENT, Mach Number

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 possess 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

A nozzle (from nose, meaning 'small spout') is a tube of varying cross-sectional area (usually axisymmetric) aiming at increasing the speed of an outflow, and controlling its direction and shape. Nozzle flow always generates forces associated to the change in flow momentum, as we can feel by handholding a hose and opening the tap. In the simplest case of a rocket nozzle, relative motion is created by ejecting mass from a chamber backwards through the nozzle, with the reaction forces acting mainly on the opposite chamber wall, with a small contribution from nozzle walls. As important as the propeller is to shaft-engine propulsions, so it is the nozzle to jet propulsion, since it is in the nozzle that thermal energy (or any other kind of high-pressure energy source) transforms into kinetic energy of the exhaust, and its associated linear momentum producing thrust.

The flow in a nozzle is very rapid (and thus adiabatic to a first approximation), and with very little frictional loses (because the flow is nearly one-dimensional, with a favorable pressure gradient except if shock waves form, and nozzles are relatively short), so that the isentropic model all along the nozzle is good enough for preliminary design. The nozzle is said to begin where the chamber diameter begins to decrease (by the way, we assume the nozzle is axisymmetric, i.e. with circular cross-sections, in spite that rectangular cross-sections, said two-dimensional nozzles, are sometimes used, particularly for their ease of directionability). The meridian nozzle shape is irrelevant with the 1D isentropic model; the flow is only dependent on cross-section area ratios.

A. Real Nozzle Flow Departs From Ideal (Isentropic) Flow On Two Aspects

Non-adiabatic effects. There is a kind of heat addition by non-equilibrium radical-species recombination, and a heat removal by cooling the walls to keep the strength of materials in longduration rockets (e.g. operating temperature of cryogenic SR-25 rockets used in Space Shuttle is 3250 K, above steel vaporization temperature of 3100 K, not just melting, at 1700 K). Short duration rockets (e.g. solid rockets) are not actively cooled but rely on ablation; however, the nozzle-throat diameter cannot let widen too much, and reinforced materials (e.g. carbon, silica) are used in the throat region. There is viscous dissipation within the boundary layer, and erosion of the walls, what can be critical if the erosion widens the throat cross-section, greatly reducing exit-area ratio and consequently thrust. Axial exit speed is lower than calculated with the one-dimensional exit speed, when radial outflow is accounted for.

1) *Spray Nozzle*: Many nozzles produce a very fine spray of liquids. Atomizer nozzles are used for spray painting, perfumes, carburetors for internal combustion engines, spray on deodorants, antiperspirants and many other similar uses. Air-Aspirating Nozzle uses an opening in the cone shaped nozzle to inject air into a stream of water-based foam (CAFS/AFFF/FFFP) to make the concentrate "foam up". Most commonly found on foam extinguishers and foam handlines. Swirl nozzles inject the liquid in tangentially, and it spirals into the center and then exits through the central hole. Due to the vertexing this causes the spray to come out in a cone shape.
2) *Ram Jet Nozzle*: Ramjet, sometimes referred to as a flying stovepipe or an athodyd (aero thermodynamic duct), is a form of airbreathing jet engine that uses the engine's forward motion to compress incoming air without an axial compressor or a centrifugal compressor. Because ramjets cannot produce thrust at zero airspeed, they cannot move an aircraft from a standstill. A ramjet-powered vehicle, therefore, requires an assisted take-off like a rocket assist to accelerate it to a speed where it begins to produce thrust. Ramjets work most efficiently at supersonic speeds around Mach 3 (2,300 mph; 3,700 km/h). This type of engine can operate up to speeds of Mach 6 (4,600 mph; 7,400 km/h). Ramjets can be particularly useful in applications requiring a small and simple mechanism for high- speed use, such as missiles. Weapon designers are looking to use ramjet technology in artillery shells to give added range; a 120 mm mortar shell, if assisted by a ramjet, is thought to be able to attain a range of 35 km (22 mi). They have also been used successfully, though not efficiently, as tip jets on the end of helicopter rotors.

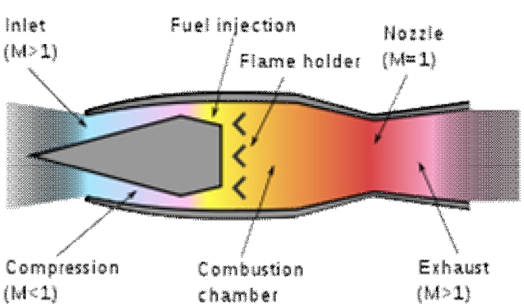

Fig 1. Ramjet Nozzle

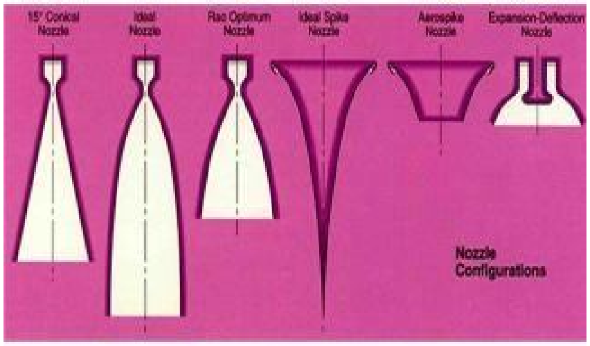

Fig 2. conical nozzles

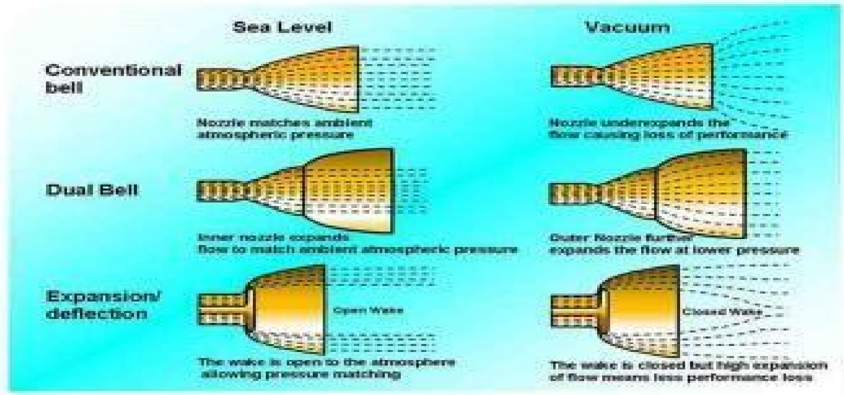

Fig 3. Bell and Dual Bell

3) *Conical Nozzles:* Used in early rocket applications because of simplicity and ease of construction. Cone gets its name from the fact that the walls diverge at a constant angle. A small angle produces greater thrust, because it maximizes the axial component of exit velocity and produces a high specific impulse. Penalty is longer and heavier nozzle that is more complex to build. At the other extreme, size and weight are minimized by a large nozzle wall angle – Large angles reduce performance at low altitude because high ambient pressure causes overexpansion and flow separation. Primary Metric of Characterization: Divergence Loss
4) *Bell and Dual Bell*: The Bell-shaped or contour nozzle is probably the most commonly used shaped rocket engine nozzle. It has a high angle expansion section (20 to 50 degrees) right behind the nozzle throat; this is followed by a gradual reversal of nozzle contour slope so that at the nozzle exit the divergence angle is small, usually less than a 10-degree half angle. An ideal nozzle would direct all of the gases generated in the combustion chamber straight out the nozzle. That would mean the momentum of the gases would be axial, imparting the maximum thrust to the rocket. In fact, there are some non-axial components to the momentum. In terms of a momentum vector, there is an angle between the axis of the rocket engine and the gas flow. As a result, the thrust is lowered by varying amounts. The Bell or Contour shape is designed to impart a large angle expansion for the gases right after the throat. The nozzle is then curved back in to give a nearly straight flow of gas out the nozzle opening. The contour used is rather complex. The large expansion section near the throat causes expansion shock waves. The reversal of the slope to bring the exit to near zero degrees causes compression shock waves. A properly designed nozzle will have these two sets of shock waves coincide and cancel each other out. In this way, the bell is a compromise between the two extremes of the conical nozzle since it minimizes weight while maximizing performance.

II. LITERATURE REVIEW

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 temperature. 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 possess 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 Lavals turbine had to run at an impractically high speed. But for rockets the de Laval nozzle was just what was needed. Many researchers have done the research on the nozzles for obtaining optimized conditions of which some of the research are as following: -

Bogdan-Alexandru Belega et-al [1] said that the Nozzle is a device designed to control the rate of flow, speed, direction, mass, shape, and/or the pressure of the stream that exhaust from them. Nozzles come in a variety of shapes and sizes depending on the mission of the rocket, this is very important for the understanding of the performance characteristics of rocket. By the proper geometrical design of the nozzle, the exhaust of the propellant gases will be regulated in such a way that maximum effective rocket velocity can be reached. Convergent divergent nozzle is the most commonly used nozzle since in using it the propellant can be heated in combustion chamber. After getting heated the propellant first converges at the throat of the nozzle and then expands under constant temperature in the divergent part. In the present paper, flow through the convergent divergent nozzle study is carried out by using a finite volume rewarding code, FLUENT 6.3. The nozzle geometry modeling and mesh generation has been done using GAMBIT 2.4 Software. Computational results are in good acceptance with the experimental results taken from the literature.

P. Vinod Kumar et-al [2] Nozzle is a device designed to control the rate of flow, speed, direction, mass, shape, and/or the pressure of the Fluid that exhaust from them. Convergent-divergent nozzle is the most commonly used nozzle since in using it the propellant can be heated incombustion chamber. In this project we designed a new Tri-nozzle to increase the velocity of fluids flowing through it. It is designed based on basic convergent-Divergent nozzle to have same throat area, length, convergent angle and divergent angle as single nozzle. But the design of Tri-nozzle is optimized to have high expansion co-efficient than

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single nozzle without altering the divergent angle. In the present paper, flow through theTri-nozzle and convergent divergent nozzle study is carried out by using SOLID WORKS PREMIUM 2014.The nozzle geometry modeling and mesh generation has been done using SOLID WORKS CFD Software. Computational results are in goodacceptance with the experimental results taken from the literature.

Sudhir Singh Rajput et-al [3] said that the current research work is related to the computational fluid dynamic analysis of two-dimensional convergent-divergent nozzle in Ansys software. It using the CVM (control volume method) to solve the governing equation of fluid flow problem formulated under the given boundary condition. The basic aim of the current study is to determine the most suitable or optimum configuration of convergent-divergent angle in DC Nozzle. The parameter of a nozzle is taken according to the DC nozzle geometry. The different configuration has made by vary angle from 15 to 40 degree at the step of 5 degrees for Convergent angle and for divergent angle, it varies from 12.5 degrees to 20 degrees at the step of 2.5 degrees. The analysis was performed in the fluent workbench of ansys software. The input data for the nozzle is taken as the temperature of exhaust gas and pressure at the inlet. The output data is obtained by fluent in the form of temperature plot and pressure distribution and velocity gradient and Mach number are calculated for each combination.

Nikhil d et-al [4] said that de Laval nozzles are mechanical devices which are used to convert the thermal and pressure energy into useful kinetic energy. The values of temperature, pressure and velocity should be available at every section of the nozzle so as to design the nozzle shape, insulation and cooling arrangements. This paper aims at providing theoretical formulae to calculate the above. The validation of these formulae is carried out using the Computational Fluid Dynamics (CFD) software ANSYS Fluent.

III. DESIGN AND MODELLING OF CONVERGENT DIVERGENT NOZZLE USING SOLID WORKS DESIGN MODULE

A. Dimensional Parameters for designing Convergent Divergent Nozzle

The Geometry of the nozzle was created using SolidWorks module by using the following parameters shown in the table 1 and in the fig 4

Table 1 Design parameters

Parameter	Dimensional quantity
Inlet diameter	25mm
Throat diameter	10mm
Exit diameter	35mm
Divergent angle	11.6^{o} ,12.5^{o},14.4^{o},15.6^{o},17.7^{o}

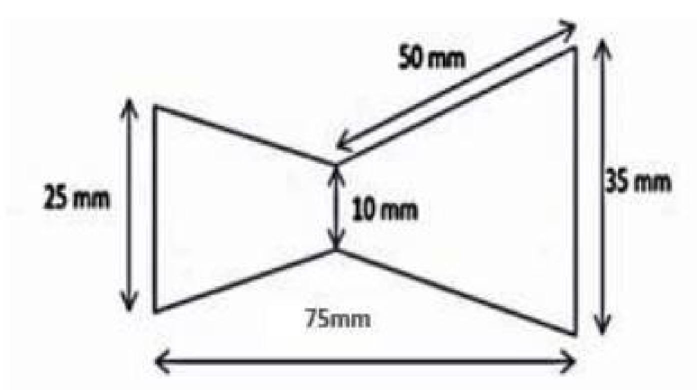


Fig4. Outline drawing of convergent divergent nozzle

B. Two-Dimensional Modelling of the Convergent Divergent nozzle

The designing of the Convergent Divergent nozzle is carried out with the help of the SolidWorks module method with standard dimensions from the literature. The standard model is being designed in the SolidWorks 2016 module by drawing the 2-D model of the convergent divergent nozzle with the known dimensions as shown:

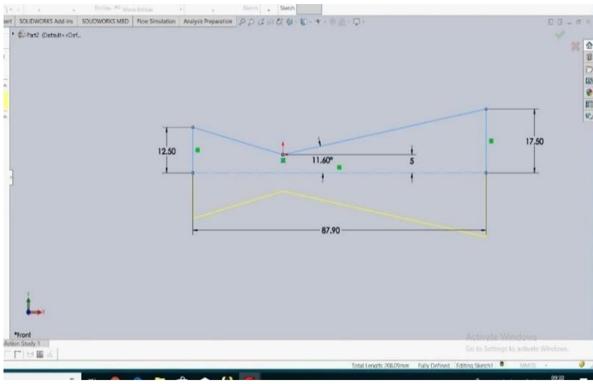


Fig 5. 2-D design of the convergent divergent nozzle

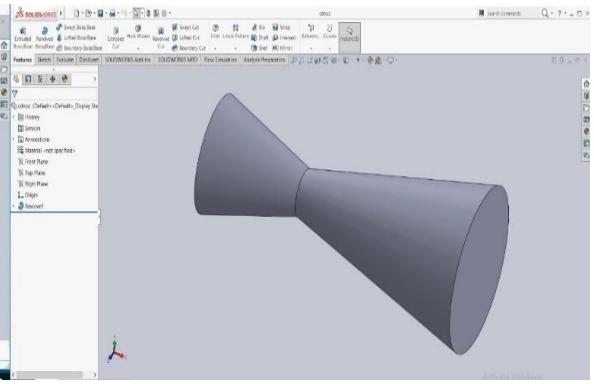
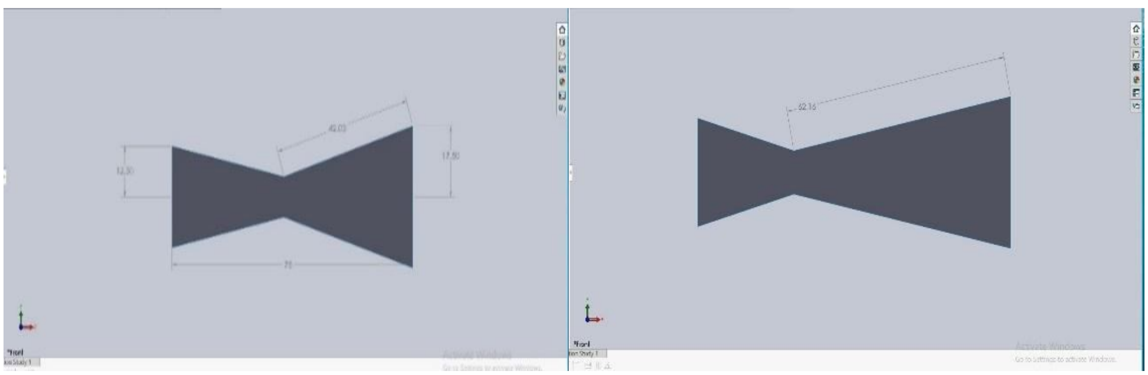
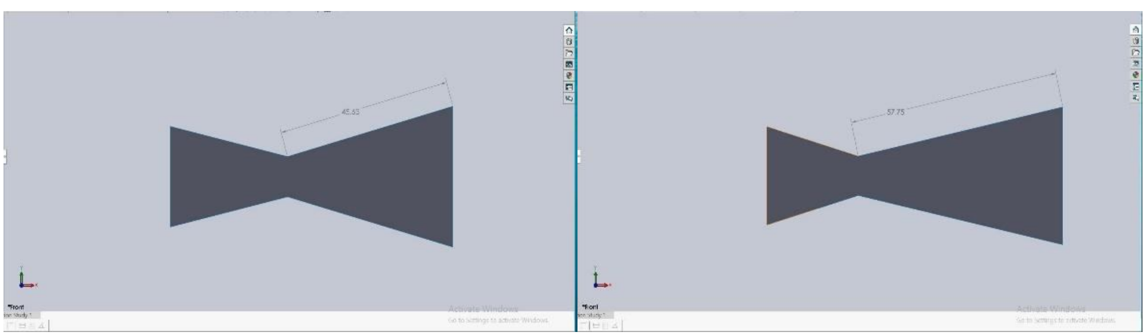


Fig 6. 3-D model of the convergent divergent nozzle



(a) Angle 12.5^{0} (b)Angle 14.4^{0}



(c) Angle 15.6^{0} (d)Angle 17.7^{0}

Fig 7. (a-b) Design of C-D nozzles having different divergent angle.

IV. CFD ANALYSIS OF THE CONVERGENT DIVERGENT NOZZLE

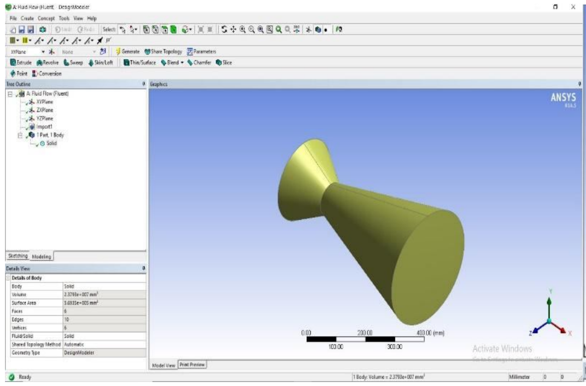
The Design of the Convergent Divergent Nozzle is made in the SolidWorks module. The 2-D outline is made in the SolidWorks module and mirror command is used for the completion of the nozzle along the axis. The complete 3-D nozzle is made using the revolve feature along the axis. The various nozzles of different diverging angles are made by changing the divergent angle of the nozzle keeping the length. The completed geometry is imported in the ANSYS FLUENT module and the analysis is carried out for different inputs of pressures and the parameters like Velocity, Temperature, Mach number and Density are studied from the results obtained.

A. Analysis of the Convergent Divergent Nozzle

The designing of the Convergent Divergent nozzle is carried out with the help of the SolidWorks module method with standard dimensions from the literature. The standard model is being designed in the SolidWorks 2016 module by drawing the 3-D model of the convergent divergent nozzle with the known dimensions of various divergent angles and are been imported in the ANSYS FLUENT module and the analysis is carried out as the following procedure

B. Import of the Geometry in ANSYS FLUENT Module

The Geometry created in the SolidWorks Module is imported in the ANSYS FLUENT Module by selecting the geometry in the FLUENT module and update the geometry as shown in the fig 8



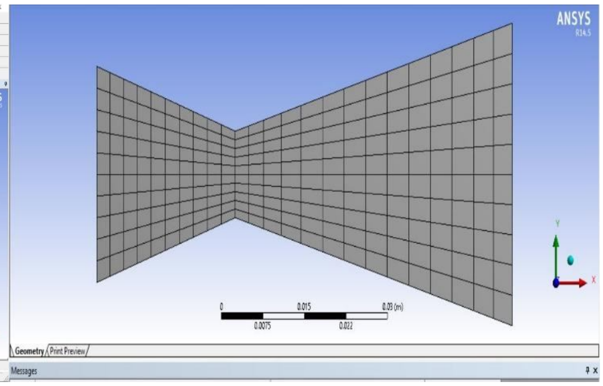


Fig 8. Geometry Import in FLUENT Module   Fig 9.Mesh generation of the convergent divergent nozzle

C. Mesh generation of the Geometry

Create named selections as inlet, outlet and walls by using named selections feature and selecting the respective edges. Then insert edge sizing feature for each of the named selections and adjust the number of divisions on edge as 50. The mesh obtained initially will be unstructured mesh and cannot be used to obtain accurate results. Since the edges are prismatic the mesh can be converted into structured meshing by using Mapped Face Meshing. Now insert Mapped face meshing feature and select the target geometry for the mesh. Under Sizing : on proximity and curvature, Relevance : medium , Smoothening : high, Finally, click on generate to create the mesh for the selected geometry

D. Solution Setup in the ANSYS FLUENT Module

Table2 Inlet Boundary Conditions

Gauge Pressure	600000 Pascal
Mach Number	0.6
X-Component of Flow Direction	1
Y-Component Of Flow Direction	0

T able 3. Outlet Boundary Conditions

Gauge Pressure	1
Backflow Direction Specification	Normal to Boundary

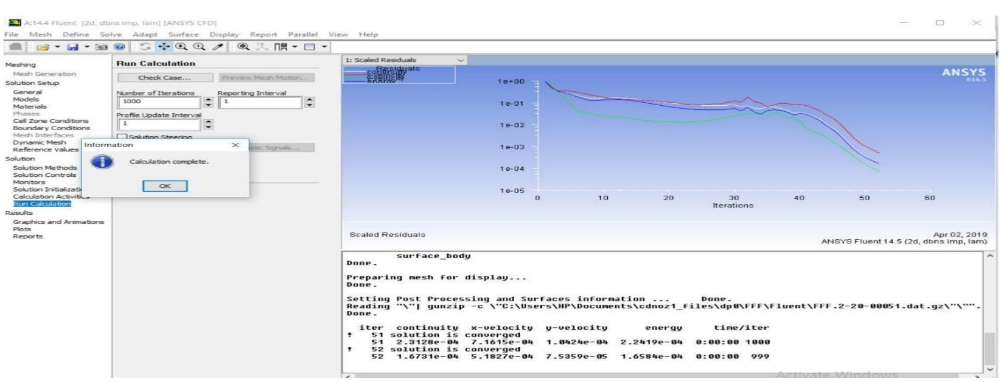


Fig 10. Post Processing Setup Calculations

E. Solution Calculations and Results

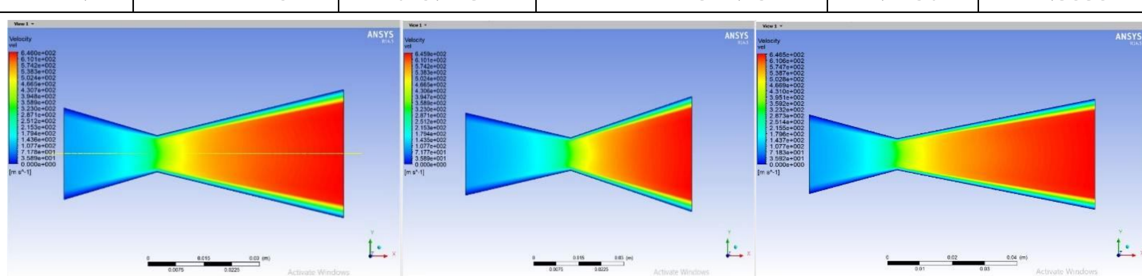
The Solution is made to run for the given number of iterations and the convergence of the solution is checked and the results are plotted. The results of the analysis carried out in the Setup feature are been plotted for various contours i.e., Pressure contour, Velocity Contour, Temperature Contour, Mach number Contour and Density Contour

V. RESULTS AND DISCUSSIONS

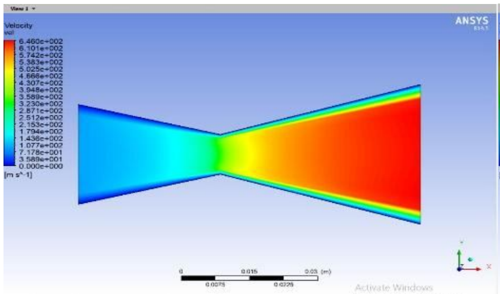
The Divergence angle of the Convergent Divergent Nozzle is varied from the standard dimensions obtained from the literature and the flow analysis is carried out in the ANSYS FLUENT Module for varying input pressures i.e., at 3 bar, 6 bar,9bar,12 bar and 15 bar. The contours of the Velocity, Temperature, Mach number and Density are obtained from the analysis and the effect of these change in Divergence Angle is studied by plotting the graphs between the output parameters i.e., Velocity, Temperature, Mach No, Density and Angle of Divergence.

Table 5. Comparison of Divergent angles with various parameters of convergent divergent nozzle at different Pressures

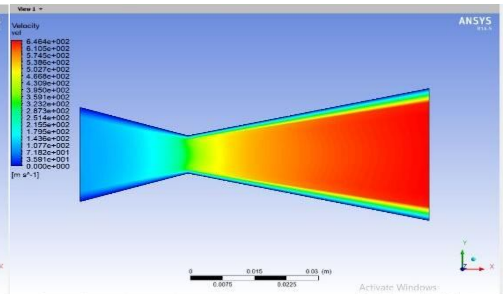
Angle (Degree)	Inlet Pressure (Bar)	Velocity (m/s)	Temperature (^oC)	Mach No	Density (Kg/m^3)
11.6	3	646.5	342.1	2.752	0.622
12.5	3	646.4	342.2	2.748	0.614
14.4	3	646.02	342.2	2.743	0.601
15.6	3	646	341.8	2.741	0.592
17.7	3	645.9	341.7	2.733	0.597
11.6	6	649.726	343.1	2.7647	1.08859
12.5	6	649.59	343.24	2.7601	1.07494
14.4	6	649.26	343.25	2.7554	1.05174
15.6	6	649.32	342.85	2.754	1.03617
17.7	6	649.23	342.73	2.7455	1.0438
11.6	9	649.7	343.09	2.7646	1.5067
12.5	9	649.629	343.24	2.7602	1.5023
14.4	9	649.22	343.24	2.7555	1.491
15.6	9	649.35	342.848	2.7542	1.485
17.7	9	649.29	342.73	2.7456	1.49
11.6	12	649.71	343.09	2.76467	2.02
12.5	12	649.643	343.24	2.7602	1.995
14.4	12	649.28	343.24	2.755	1.951
15.6	12	649.366	342.848	2.7543	1.923
17.7	12	649.22	342.73	2.7456	1.9372
11.6	15	649.723	343.099	2.76473	2.48641
12.5	15	649.649	343.24	2.76031	2.45539
14.4	15	649.25	343.24	2.7556	2.402
15.6	15	649.37	342.848	2.75432	2.36645
17.7	15	649.223	342.73	2.7456	2.3838



(a) Angle 11.6^o (b) Angle 12.5^o (c) Angle 14.4^o

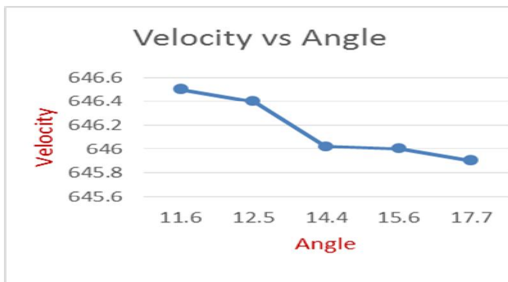


(d)Angle 15.6^{O}

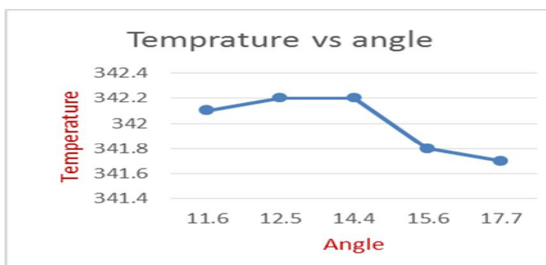


(e)Angle17.7^{O}

Fig 11. Velocity contours for various divergence angles at 3 bar pressure



(a)



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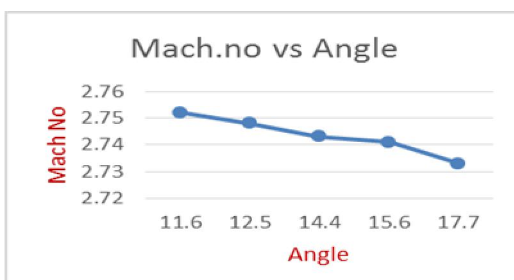
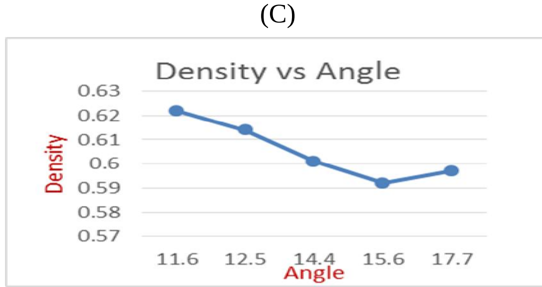


(C)



(d)

Fig 12. Graphs for various parameters vs divergence angles at 3 bar pressures

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A. Variation Of Velocity, Temperature, Mach Number And Density For Various Divergence Angles At 3 Bar Pressure

The maximum velocity of flow through convergent divergent nozzle is obtained with the C-D Nozzle having a divergence angle of 11.6^{o} and there is equal velocity obtained for the nozzles having divergence angle of 14.4^{o} and 15.6^{o} and the minimum velocity of flow is obtained for the nozzle having divergence angle of 17.7^{o}.The Temperature is minimum at the nozzle having divergence angle of 17.7^{o} and equal temperatures are attained for both the nozzles having divergence angle of 12.5^{o} and 14.4^{o} and the maximum temperature is obtained for the nozzle having divergence angle of 14.4^{o}. The Mach Number is maximum for the nozzle having divergence angle of 11.6^{o} and minimum ach number is for the nozzle having divergence angle of 17.7^{o}. The Density is minimum for the C-D nozzle having divergence angle 15.6^{o} and maximum for the nozzle having the divergence angle of 11.6^{o}.

B. Variation Of Velocity, Temperature, Mach Number And Density For Various Divergence Angles At 6 Bar Pressure

The maximum velocity of flow through convergent divergent nozzle is obtained with the C-D Nozzle having a divergence angle of 11.6^{o} and there is an increase in velocity obtained from the nozzles having divergence angle of 14.4^{o} and 15.6^{o} and the minimum velocity of flow is obtained for the nozzle having divergence angle of 17.7^{o}. The Temperature is minimum at the nozzle having divergence angle of 17.7^{o} and equal temperatures are attained for both the nozzles having divergence angle of 12.5^{o} and 14.4^{o} and the maximum temperature is obtained for the nozzle having divergence angle of 14.4^{o}.The Mach Number is maximum for the nozzle having divergence angle of 11.6^{o} and minimum Mach number is for the nozzle having divergence angle of 17.7^{o}. The Density is minimum for the C-D nozzle having divergence angle 15.6^{o} and maximum for the nozzle having the divergence angle of 11.6^{o}.

C. Variation Of Velocity, Temperature, Mach Number And Density For Various Divergence Angles At 9 Bar Pressure

The maximum velocity of flow through convergent divergent nozzle is obtained with the C-D Nozzle having a divergence angle of 11.6^{o} and there is an increase in velocity obtained from the nozzles having divergence angle of 14.4^{o} and 15.6^{o} and the minimum velocity of flow is obtained for the nozzle having divergence angle of 17.7^{o}.The Temperature is minimum at the nozzle having divergence angle of 17.7^{o} and equal temperatures are attained for both the nozzles having divergence angle of 12.5^{o} and 14.4^{o} and the maximum temperature is obtained for the nozzle having divergence angle of 14.4^{o}. The Mach Number is maximum for the nozzle having divergence angle of 11.6^{o} and minimum Mach number is for the nozzle having divergence angle of 17.7^{o}. The Density is minimum for the C-D nozzle having divergence angle 15.6^{o} and maximum for the nozzle having the divergence angle of 11.6^{o}.

D. Variation Of Velocity, Temperature, Mach Number And Density For Various Divergence Angles At 12 Bar Pressure

The maximum velocity of flow through convergent divergent nozzle is obtained with the C-D Nozzle having a divergence angle of 11.6^{o} and there is an increase in velocity obtained from the nozzles having divergence angle of 14.4^{o} and 15.6^{o} and the minimum velocity of flow is obtained for the nozzle having divergence angle of 17.7^{o}. The Temperature is minimum at the nozzle having divergence angle of 17.7^{o} and the maximum temperature is obtained for the nozzle having divergence angle of 14.4^{o}. The Mach Number is maximum for the nozzle having divergence angle of 11.6^{o} and minimum Mach number is for the nozzle having divergence angle of 17.7^{o}. The Density is minimum for the C-D nozzle having divergence angle 15.6^{o} and maximum for the nozzle having the divergence angle of 11.6^{o}.

E. Variation Of Velocity, Temperature, Mach Number And Density For Various Divergence Angles At 15 Bar Pressure

The maximum velocity of flow through convergent divergent nozzle is obtained with the C-D Nozzle having a divergence angle of 11.6° and there is an increase in velocity obtained from the nozzles having divergence angle of 14.4° and 15.6° and the minimum velocity of flow is obtained for the nozzle having divergence angle of 17.7°.The Temperature is minimum at the nozzle having divergence angle of 17.7° and equal temperatures are attained for both the nozzles having divergence angle of 12.5° and 14.4° and the maximum temperature is obtained for the nozzle having divergence angle of 14.4°.The Mach Number is maximum for the nozzle having divergence angle of 11.6° and minimum Mach number is for the nozzle having divergence angle of 17.7°.The Density is minimum for the C-D nozzle having divergence angle 15.6° and maximum for the nozzle having the divergence angle of 11.6°.

VI. CONCLUSION

The Design of the Convergent Divergent nozzle has been done in the SolidWorks Module and the various nozzles of different divergence angle are created using the SolidWorks Module and the computer aided solutions are developed using Fluent Analysis. Solutions are evaluated for different divergent angles of the Convergent Divergent nozzle corresponding Velocity, Mach Number, Density, Temperature are determined. The Variation in increase in Inlet pressure with Mach Number was found to be identical from the Inlet throat. With the corresponding increase of inlet pressure corresponding velocity also increases. Variation in Density decrease with decrease in Inlet pressure. Temperature increases with increasing Inlet pressures.

1) Solutions are evaluated at different Divergent angles of the Convergent Divergent Nozzle corresponding to the Velocity, Mach Number, Density and Temperature.
2) The angle of divergence for the divergent portion is varied and its corresponding parameters are studied and convergence of flow is obtained at 554 iterations using Computational Fluid Dynamics (CFD).
3) From the solutions obtained it is observed that the optimized angle for the divergence in the Convergent Divergent Nozzle is $14^{\circ} - 15^{\circ}$ to obtain maximum velocity and the higher propulsions for the rocket engines can be achieved with this angle.

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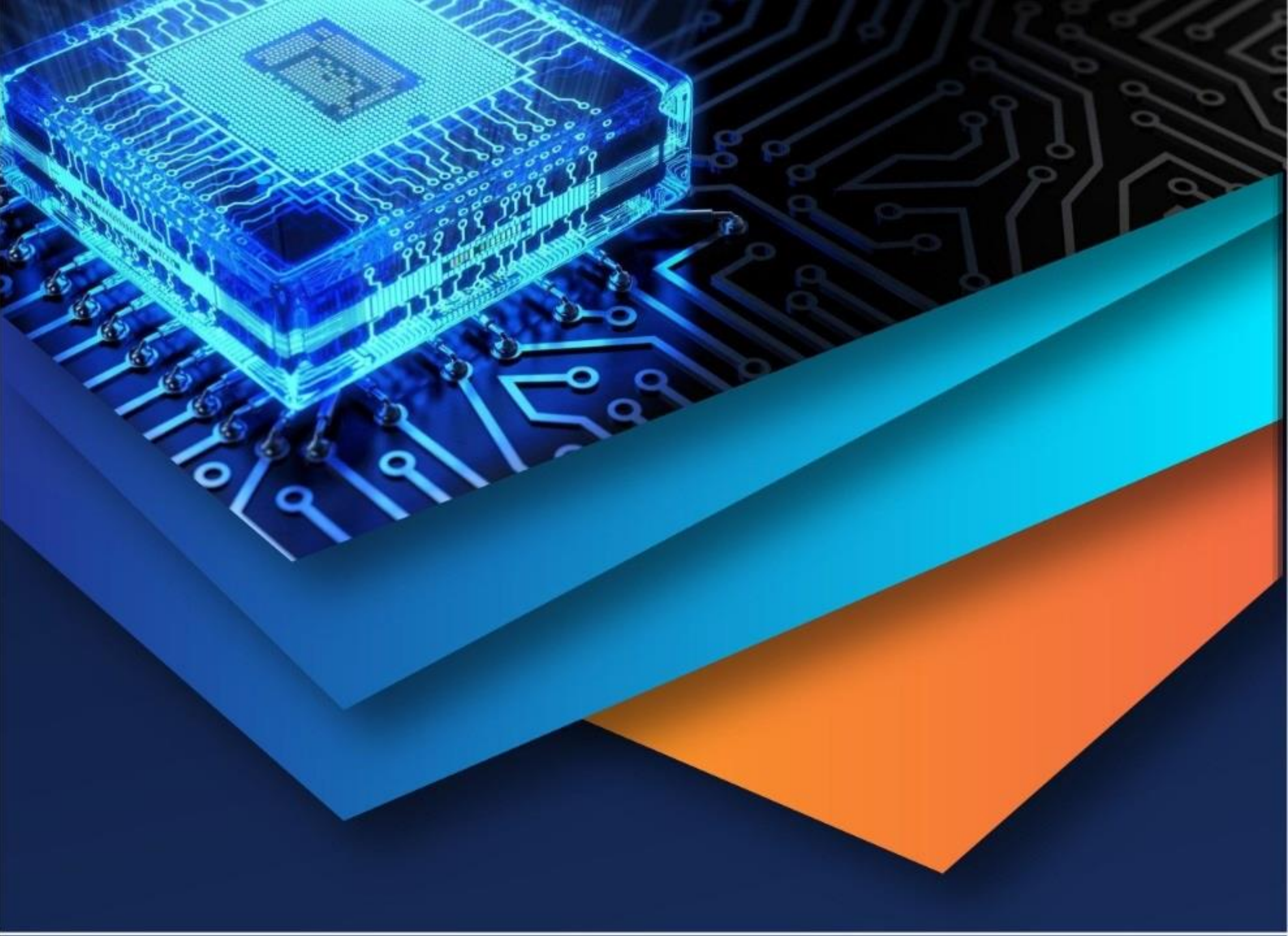

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