COMPUTATIONAL INVESTIGATION ON SUPERSONIC PROPELLING NOZZLE OF ROCKET ENGINE

A THESIS

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CERTIFICATE

This is to certify that the Major Project entitled **"*COMPUTATIONAL INVESTIGATION ON SUPERSONIC PROPELLING NOZZLE OF ROCKET ENGINE*"** is carried out by ***Gagan R Preeth (1SI18ME034), Harish G R (1SI18ME038), Hemanth C (1SI18ME040), Manjunath Gowda K R (1SI18ME052)*** bonafide students of Siddaganga Institute of Technology, Tumakuru, and submitted report in partial fulfilment of the requirement for the award of Bachelor of Engineering in Mechanical Engineering of Visvesvaraya Technological University, Belagavi during the year 2021-22. It is certified that all corrections/suggestions indicated for Internal Assessment have been incorporated in the report deposited in the departmental library. The Major Project report has been approved as it satisfies the academic requirements in respect of Major Project work prescribed for the said Degree.

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1. ....
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Dedicated to our parents, our teachers, our guide and our team mates who supported us through thick and thin during the course of theproject and to all the engineers who strive out there to build a better tomorrow……

THESIS CERTIFICATE

This is to certify that the thesis entitled **“COMPUTATIONAL INVESTIGATION ON SUPERSONIC PROPELLING NOZZLE OF ROCKET ENGINE”** submitted to the Siddaganga Institute of Technology, for the award of the degree of Bachelor **of Engineering** is a bonafide record of project work carried out by us under the supervision of **Dr. Nithesh K G**. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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ABSTRACT

A nozzle in a rocket engine propels hot exhaust to create thrust in accordance with Newton's third law of motion. The amount of thrust produced by the engine is determined by the mass flow rate through the engine, the exit velocity of the flow, and the pressure at the engine's exit. The value of these three flow variables is governed by the rocket nozzle design. In addition, the design of the nozzle is an important consideration when attempting to accomplish a maximum Mach number or supersonic speed.

Rocket nozzles typically consist of a fixed convergent part followed by a fixed divergent section. A convergent-divergent, or CD, nozzle is the name given to this arrangement of nozzles. The hot exhaust from the combustion chamber converges on the nozzle's minimum area, or throat, in a CD rocket nozzle. The high temperature, high pressure, and low velocity gas are all converted into high velocity, low pressure gas at the exit by this nozzle.

Numerical simulations of supersonic flow through the rocket's nozzle have been performed. The goal of this study is to model a 3D convergent-divergent nozzle and examine the variations in flow parameters (pressure, temperature, and Mach number) brought on by altering the convergent angles of the nozzle (24°, 26°, 28°, 30°, and 32°) while keeping the same throat and outlet diameters.

In order to determine the appropriate convergent angle, the flow characteristics variation at the nozzle exit is investigated. The Mach number and thrust at the nozzle's exit are found to be 1.7 and 13610.7N from the analysis for a convergent angle of 26°. When all of the converging angle results were taken into account, 26˚ produced the highest Thrust and Mach number, which will enhance the nozzle's performance and, as a result, increase the power and effectiveness of a propulsion system.

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CHAPTER 1

INTRODUCTION

1.1 ROCKET PROPULSION SYSTEM

The nozzle plays a crucial role in the propulsion system and is primarily responsible for accelerating the hot gases that flow through it. Along with directing and controlling pressure, it also controls the flow. It also turns the pressure energy into kinetic energy. The nozzle's performance has a big impact on the propulsion system's efficiency. Usually, there are a few distinct categories into which nozzles can be divided. Convergent-divergent nozzles are among those that are in great demand to produce the supersonic speeds required in a number of technical specializations.

The Convergent-Divergent (CD) nozzle, used in rocket engines, supersonic jet engines, and some variants of steam turbines, is a common design. It also goes by the name "de-Laval nozzle" in some contexts. The gas expands and accelerates to a speed faster than the speed of sound. The performance of this nozzle is determined by flow characteristics, which are impacted by the nozzle's geometry.

Rocket propulsion is a type of jet propulsion in which thrust is generated by ejecting stored material known as propellant. This type of propulsion is used in rockets. Rocket propulsion systems can be classified based on their energy source (chemical, nuclear, or solar), with the primary function remaining the same (booster stage, sustainer, altitude control, orbit station keeping, etc.,) The size of the vehicle (plane, missile, space vehicle, etc.), type of construction, propellant type, and number of rocket propulsion units utilized in a certain vehicle are all aspects to consider.

Rocket nozzles typically consist of a fixed convergent part followed by a fixed divergent section. A convergent-divergent, or CD, nozzle is the name given to this arrangement of nozzles. The hot exhaust from the combustion chamber converges on the nozzle's minimum area, or throat, in a CD rocket nozzle. The high temperature, high pressure, and low velocity gas are all converted into high velocity, low pressure gas at the exit by this nozzle.

1.2 CLASSIFICATION OF ROCKET PROPULSION

Rocket propulsion is classified as follows:

- Chemical rocket propulsion
- Nuclear rocket propulsion
- Electric rocket propulsion
- Solar rocket propulsion

CHEMICAL ROCKET PROPULSION

Chemical propellants are commonly used to provide exact impulse values ranging from around 175 seconds to nearly 300 seconds. Maximum active chemical propellants are potentially capable of producing accurate impulses lasting up to 400 seconds.

To be efficient, a propellant must have a high rate of combustion to produce high temperatures and must produce combustion products including simple, mild molecules like as hydrogen (the lightest), carbon, oxygen, and the lighter metals (aluminum, beryllium, lithium).

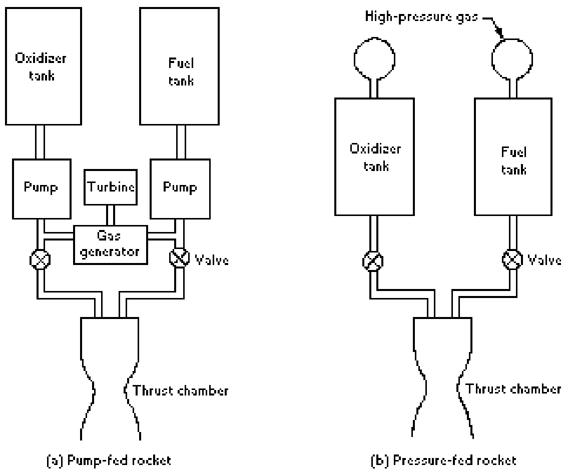


Fig 1.1: Fuel and Oxidizer feeding system [1]

The density of a propellant is another crucial element. When compared to a low-density propellant of the same weight, a dense propellant can be transported in a smaller, lighter tank.

Other criteria must be addressed when selecting propellants. Some compounds with high specific impulse cause issues in engine functioning. Some are insufficient as coolants for the heated thrust-chamber walls. Others have anomalies in combustion that make their use difficult or impossible. Some are unstable to varied degrees and cannot be properly kept or handled. Such characteristics exclude its application in rocket propulsion.

Unfortunately, practically any useful propellant is likely to be a very active chemical, thus, most propellants are corrosive, combustible, or toxic, and are frequently all three.

The availability of a rocket propellant is also important when selecting one. In rare circumstances, a completely new chemical facility is required to obtain sufficient amounts of a propellant. Furthermore, because some propellants are utilized in huge amounts, raw material availability must be considered.

It is further classified into:

- Liquid propellant
- Solid propellant
- Gaseous propellant
- Hybrid propellant

NUCLEAR ROCKET ENGINE

Nuclear rockets no longer employ any kind of combustion process. Rather, the most recent exhaust fuel line is created by sending a working fluid through a fission reactor.

Even though no power is provided to the rocket by any chemical reaction, nuclear rockets should employ some chemical as an operational fluid or propellant.

The reactor generates all of the heat. Liquid hydrogen is the best substance up to this point because the main focus is on lowering the molecular weight of the exhaust gasoline. Fission reactors, radioactive isotope decay, and fusion reactors are the three types of nuclear power sources that have been researched.

ELECTRIC ROCKET PROPULSION

Electro thermal, electro static, and electromagnetic propulsion are all explored. Electric driven rocket propulsion has the highest specific impulse of all rocket propulsion methods. Electro jet, arc jet, magneto plasma dynamic thruster, pulsed plasma thruster, corridor thruster, etc. are a few examples of electrical propulsion.

SOLAR ROCKET PROPULSION

A variety of proposals have been put up to use the Sun's radiation to provide a space spacecraft with propulsion power. Solar radiation can be used for propulsion in "open" environments even if its energy density is relatively low compared to chemical launch rockets' enormous power.

A very small amount of thrust will be sufficient to drastically change or accelerate a vehicle's trajectory once it has travelled far from Earth or another planetary body or has been placed in a satellite orbit.

1.3 PRINCIPLE OF OPERATION OF ROCKET ENGINES

The rocket, in one of its many variants, is considered the easiest way to meet space flight speed requirements. The reaction pressure created by ejecting debris from a nozzle opening at a high rate of speed is known as rocket thrust. These ejected particles may be made of solids, liquids, gases, or even bundles of radiant energy.

As long as the delivery of debris or flowing fluid persists, the engine's ability to produce thrust will experience the simplest changes. Without the ability to expel fabric, no thrust can be produced, regardless of how much power is supplied. Fabric expulsion is the essence of the thrust production.

Due to this crucial aspect, an important criterion for evaluating rocket performance is exact impulse, which measures the efficiency with which a rocket utilizes its fuel or operating fluid to generate thrust.

For gaseous flowing fluids, precision impulse can be accelerated by,

(1) Increasing combustion chamber temperatures.

(2) Increasing the proportion of lighter gases, especially hydrogen, in the exhaust.

The load of engine and running fluid box necessary in measuring the advantage of a propulsion device in particular software is the different vital aspect, because such weights have an effect on the achievable propellant fraction.

1.4 PERFORMANCE PARAMETERS

The rocket engine's performance is mostly determined by the four characteristics listed below.

1. Thrust
2. Specific impulse
3. Effective exhaust velocity
4. Characteristic velocity

All of the above criteria are mostly determined by the following:

a) The chamber pressure
b) The atmospheric pressure
c) Ratio of expansion area
d) Nozzle design and exit angle
e) The composition and mixing ratio of propellants
f) Assumption and correction in theoretical performance calculations
g) Propeller initial temperature

THRUST

The thrust is the force produced by the action of a rocket propulsion system on a vehicle. Momentum is a vector quantity defined as the product of mass multiplied by velocity.

The thrust, due to change in momentum is given below.

$$F_T = \dot{m}_e U_e + A_e \left(p_e - p_{amb}\right) \quad [2]$$

When the nozzle exit pressure equals the ambient pressure, this force represents the total propulsion force.

SPECIFIC IMPULSE

Specific impulse is the best indicator of a rocket motor's overall performance. In seconds, a specific impulse is expressed. The particular impulse is the length of time for which the rocket engine produces a thrust equal to the weight of the propellant used while the thrust and flow rate remain constant during the propellant burning.

$$I_{sp} = \frac{F_T}{\dot{m}_{ejects}} \quad [2]$$

Because the ambient pressure is taken into account in the expression for the thrust for a given engine, the specific impulse has different values on the ground and in the vacuum of space. It is crucial to specify whether the value of a certain impulse is that at sea level or in a vacuum.

EFFECTIVE EXHAUST VELOCITY

The average equivalent velocity at which propellant leaves the vehicle is known as the effective exhaust velocity.

$$c = \frac{F_T}{\dot{m}_e} = I_s g_o \quad [2]$$

CHARACTERISTIC EXHAUST VELOCITY

Characteristic velocity, which is used to compare various propellants, is a measurement of the combustion performance of a rocket engine independent of nozzle performance.

$$c = U_e + \frac{(p_e - p_a)A_e}{\dot{m}_e} \quad [2]$$

$$C^* = \frac{P_c A_t}{\dot{m}_e} \quad [2]$$

There may be a significant amount of losses in practice even though the rocket engine's theoretical performance criteria have been established. A rocket engine contains some losses, the main ones being those brought on by the ineffectiveness of the combustion process, losses from the nozzle, and losses from the pumps. The overall performance of the given impulse is impacted by the losses.

This is the ratio of the actual specific impulse (at sea level or in a vacuum) to the theoretical specific impulse acquired with a large nozzle from gases produced by a full chemical reaction.

Losses of the inner surprise waves inside the supersonic flow were reduced to a minimum by the bell-contoured nozzle. Since the 1960s, both rockets using liquid propellant and those using stable propellant have used bell-shaped nozzles. Before the transition to bell-shaped discharge nozzles, conical nozzles had been utilized often in the past. Figures 1.2 and 1.3, respectively, demonstrate how a Rao nozzle and conical nozzle are shaped.

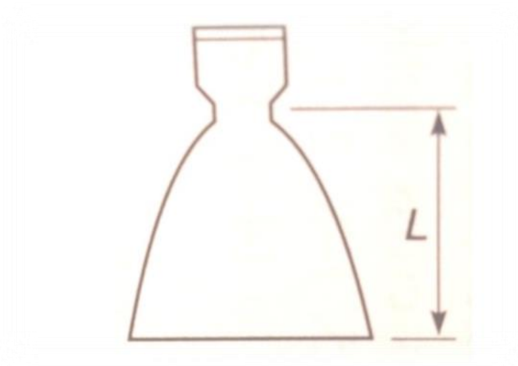


Fig 1.2: Rao nozzle [3]

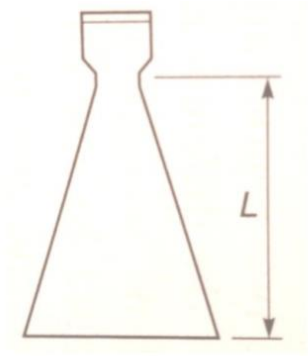


Fig 1.3: Conical Nozzle [3]

At high altitudes, an under-expanded nozzle develops when the exit pressure is higher than the surrounding pressure. Beyond the nozzle exit, the exhaust plume keeps growing, decreasing efficiency. When the outlet pressure is equal to the ambient pressure, the nozzle expands properly, resulting in optimum efficiency.

An over-expanded nozzle occurs when the exit pressure is less than the ambient pressure at low altitudes such as sea level. The exhaust plume is pinched inward in fluid separation from the walls creating compression waves or shock waves inside the diverging nozzle section. Fig 1.4 below shows the under-expanded, over-expanded, and perfectly expanded nozzles.

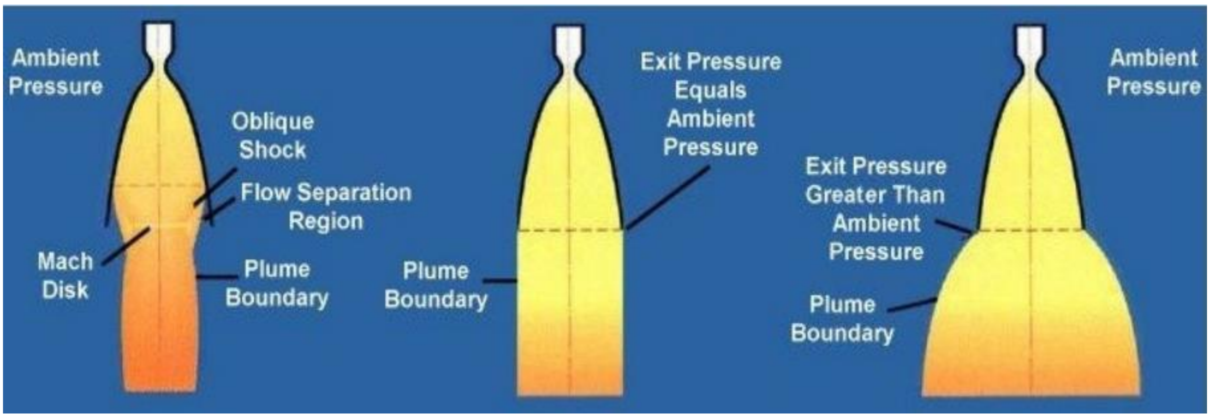


Fig 1.4: Under-Expanded, Over-Expanded, & Perfectly Expanded Nozzles [4]

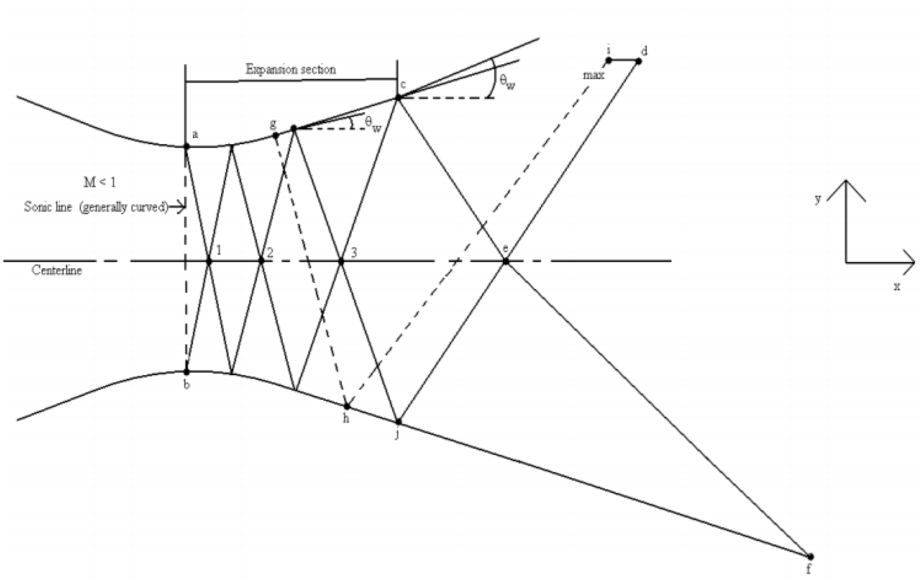


Fig 1.5: Schematic of Supersonic Nozzle Design by the MOC [5]

The most popular combustion chamber for rockets is cylindrical because it is easier to manufacture and performs better than a spherical or nearly spherical chamber. Figure following illustrates a concept sketch for a cylindrical combustion chamber.

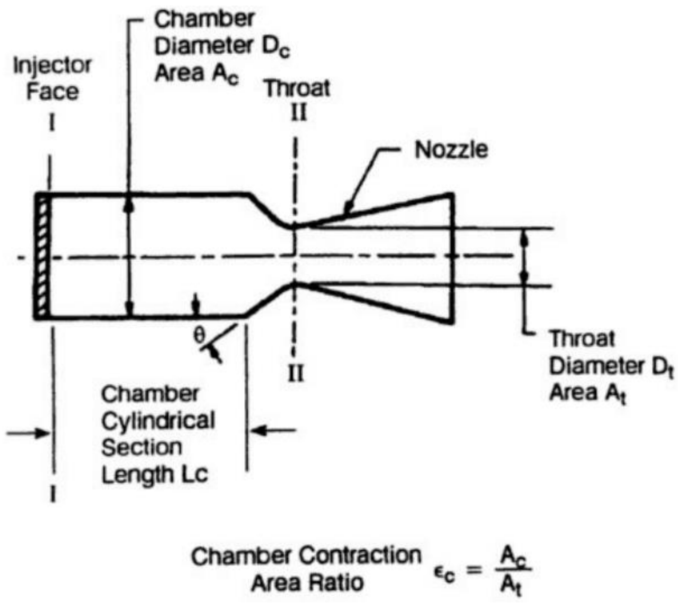


Fig 1.6: Rocket Cylindrical Combustion Chamber [6]

Liquid propellant is injected into the combustion chamber using injectors, particularly a doublet or triplet impinging flow sample configuration.

The doublet impinging flow sample performs admirably when the gasoline hollow length is the same as the oxidizer hollow length.

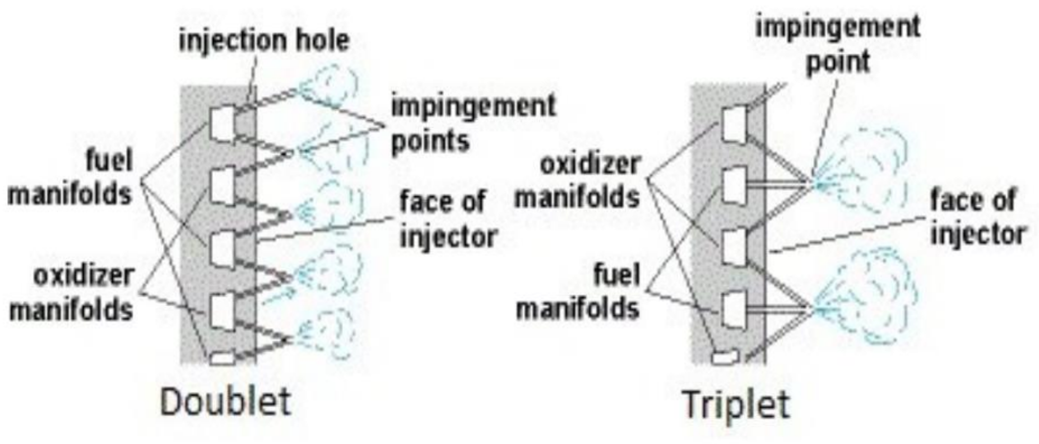


Fig 1.7**:** Schematic Diagrams of the Doublet and Triplet Injector Types [3]

CHAPTER - 2

LITERATURE SURVEY

The main reason for the invention of the nozzles was to modify the flow properties, such as pressure and velocity. A convergent-divergent (CD) nozzle was created in 1890 by Carl Gustaf Patrik de Laval that could accelerate a steam jet to supersonic speed [7].

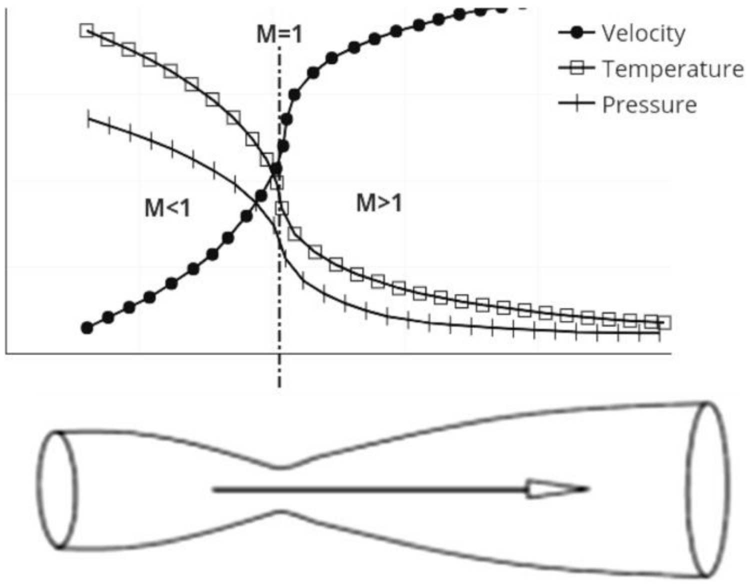


Fig 2.1: Variations in pressure, temperature, and velocity along a De Laval nozzle [7].

The principal means of propulsion for space travel is the rocket, which stores its own mass of fuel and expels it rapidly to provide thrust [8].

This thrust is created by accelerating the exhaust gases of a rocket engine to the required speed and direction [9]. Simply described the nozzle increases the amount of force by leveraging the pressure inside the combustion chamber to accelerate the combustion products to a high supersonic velocity.

The creation of cutting-edge rocket nozzles for launch vehicles is a challenging task [10]. To ensure that they perform as expected at higher altitudes, the nozzles are constructed with high area ratios.

In addition to the recently developed multi nozzle grid (MNG), there are many different rocket nozzle designs available, including ideal, conical, bell, plug, expansion-deflection (E-D), and dual bell [11].

Due to its simplicity and ease of production, the conical form has historically been the most popular shape for rocket nozzles [12].

The area ratio and exit velocity of a conical nozzle are practically one-dimensional (1D), but the flow is not axial over the output area, leading to performance loss from flow divergence [13].

Conical type short nozzles are used in small thrust and solid rocket boosters because of their significant divergence losses, which are preferred over aerodynamic performance [14].

The nozzle wall can be contoured to reduce thrust loss; this design is known as a bell nozzle. This is so that the flow can be controlled to turn more toward the axial direction [15].

The plug nozzle is a form of rocket nozzle that accommodates for altitude, as opposed to a standard CD nozzle that expands the flow to a set area ratio regardless of the free stream circumstances. The free jet boundary, which acts as a plug nozzle's virtual outer wall, expands to meet the free stream ambient pressure [16].

The flow from the chamber is directed radially outward and away from the nozzle axis in the E-D nozzle. The flow is directed towards the outer diverging nozzle wall's curved contour [17].

A more modern concept known as Multi Nozzle Grid (MNG) proposes the use of a short, light plate with several small nozzles rather than a long, heavy single nozzle. A MNG with 100 nozzlettes is ten times smaller than a single nozzle of the same size, and the length savings are proportional to the square root of the number of small nozzles (nozzlettes) [18].

To overcome the complexity of experimental approaches, numerical methods are used with the aid of computer analysis software. CFD approach is carried out using ANSYS FLUENT to simulate the nozzle flow. Since the divergent angle affects performance, the conical nozzle has been tested so far at divergent angles of 7, 13, and 15, while maintaining the same intake and outlet diameters, and dependent parameters such as Mach number, static pressure, and shocks are reported [19].

Conical nozzle visualizations of supersonic expansion through CD nozzles produced results that were similar to experimental Schlieren photos and average shadowgraph images [20, 21].

An estimate of the exit pressure ratio is obtained by using reversible adiabatic and normal shock relations. With this exit pressure ratio, a more refined verification is done by computational analysis using ANSYS Fluent software for a contour nozzle with exit Mach number 5.5. The spalart Allmaras and k-epsilon model were used for turbulence modeling. Divergent nozzle contours were plotted for different exit mach numbers. The estimated exit area was similar to the theoretical one. The contours obtained through fluent simulation were close to the theoretical values of mach number at the exit [22].

ANSYS Fluent, software for computational fluid dynamics (CFD), is used to validate these formulas. CFD considers the factors like boundary layer effects, shock waves, radial velocity component and so on, which leads to some variance from theoretical results [23].

The challenge for designers of rocket nozzles is to continually find ways to harvest a greater specific impulse with a smaller size nozzle while optimizing cost savings and reducing structural complexity. Some of the most desired characteristics of a rocket nozzle include reduced weight, maximum performance, and simplicity of construction.

The detailed literature analysis demonstrates, each design has unique strengths and disadvantages, and no design comes out as clearly superior to the others.

CHAPTER – 3

CFD MODELING AND ANALYSIS

3.1 INTRODUCTION

The computational fluid dynamics (CFD) tool is an engineering tool that assists in experimenting. In the computational fluid dynamics (CFD) analysis of the nozzle, the following processes were carried out: modeling, meshing, pre-processing, solution, and post-processing.

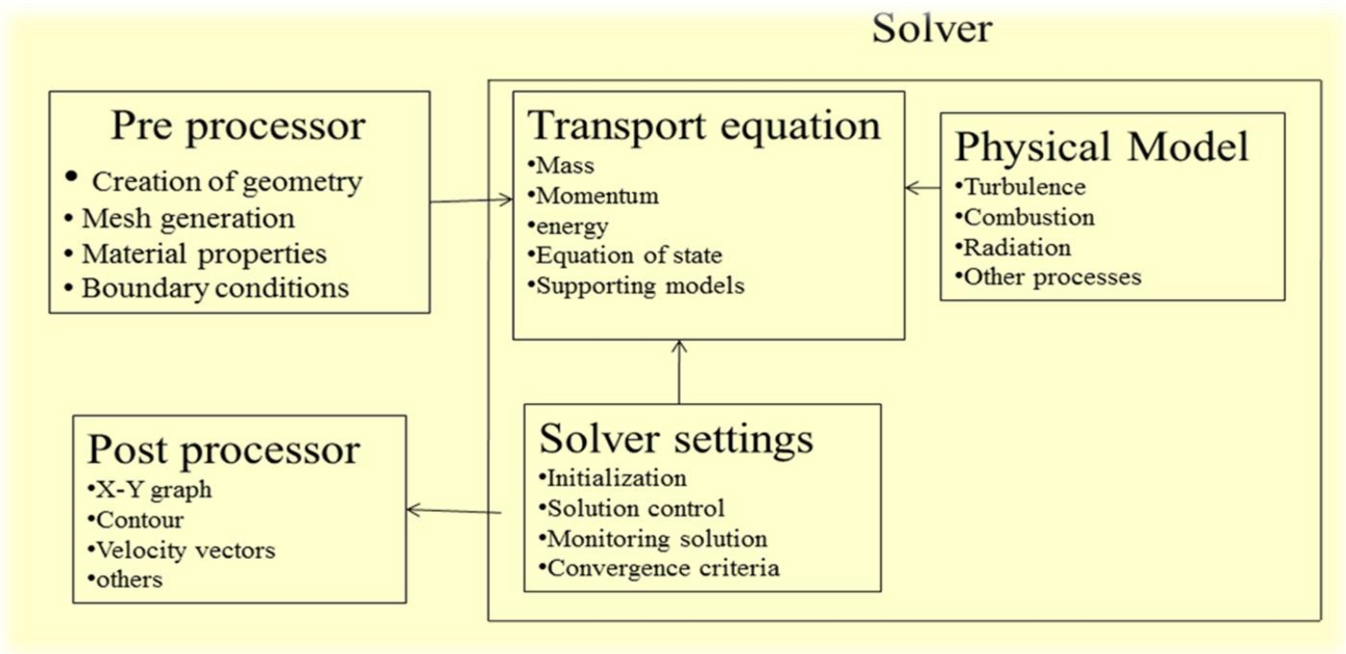


Fig 3.1: Main Elements of CFD Analysis [3]

This project comprises the process of numerical research for the characteristics of several convergent angles in nozzle by using CFD. The approach includes the procedure sequentially which was carried out is as shown in the fig 3.1.

3.2 METHODOLOGY

Modeling and flow analysis of 3-D models of the nozzle were carried out using CATIA and ANSYS software.

The methodology includes the process sequentially which carried out, this project includes the process of numerical investigation with different convergent angles (24°, 26°, 28°, 30°, 32°) in nozzle by ANSYS CFD.

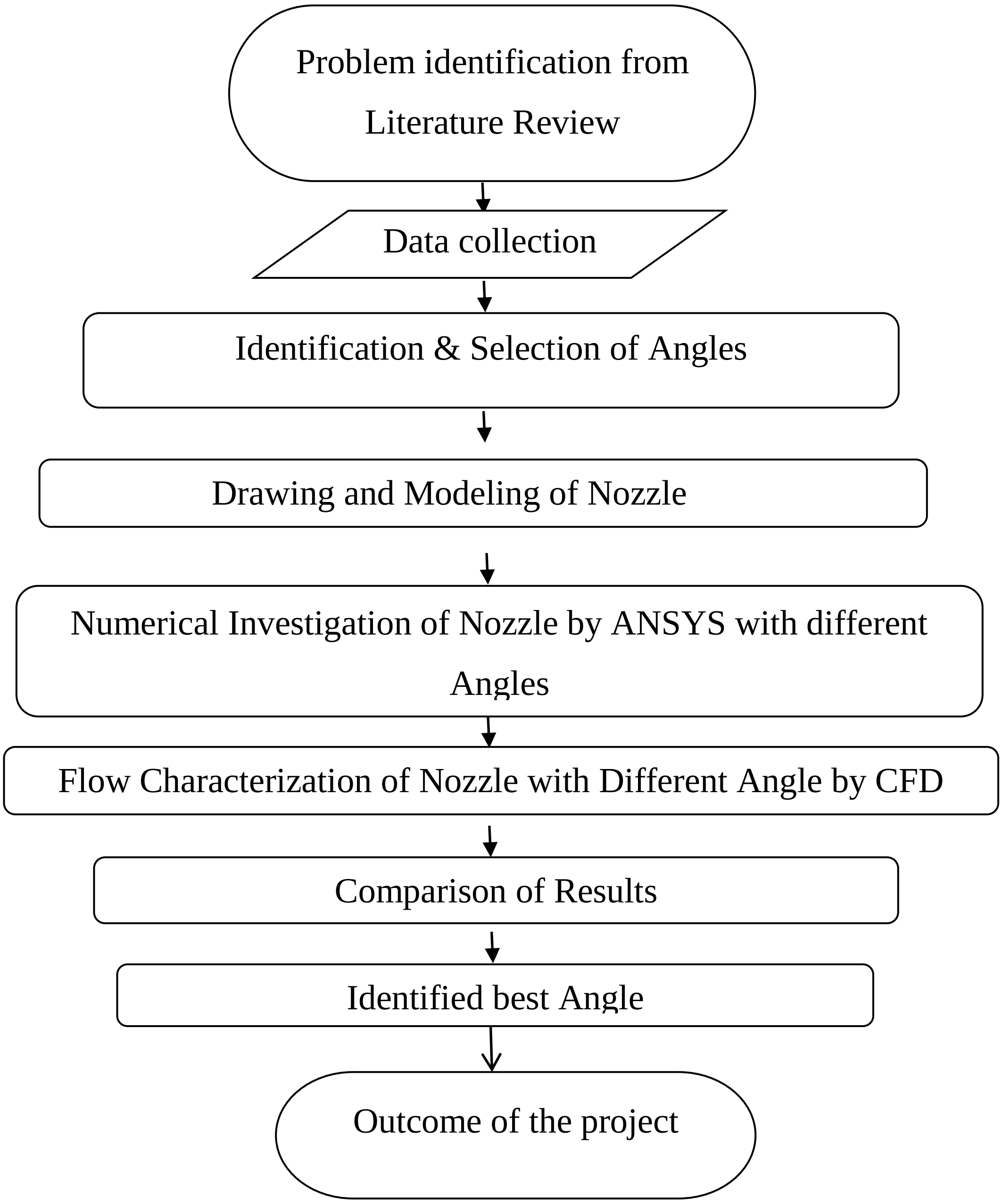


Fig 3.2: Flow chart

3.3 MODELING: Using CATIA and ANSYS software, 3-D models of the nozzle were modeled and their flow was examined. The dimensions of the CD nozzle are presented in the table given below.

Table 3.1: Nozzle dimensions

Parameters	**Dimensions**				
Convergence angle (deg)	24	26	28	30	32
Divergence angle (deg)	15				
Inlet diameter (mm)	91.17	94.14	97.22	100.41	103.74
Throat diameter (mm)	60				
Outlet diameter (mm)	140				

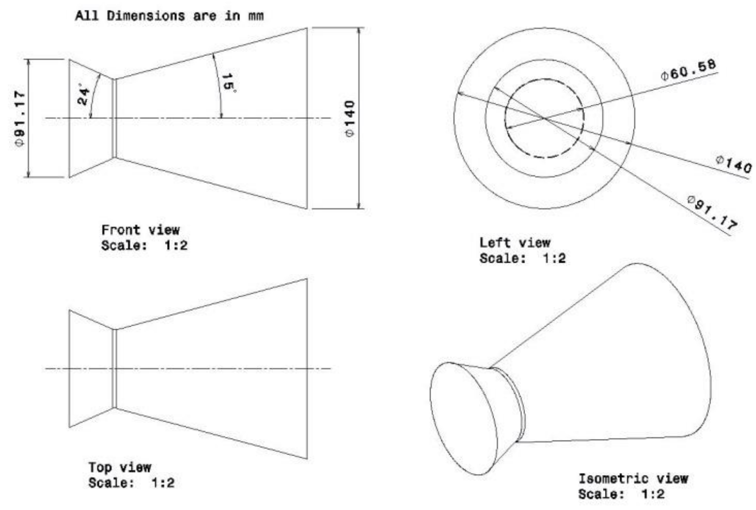


Fig 3.3: Dimensions of Nozzle

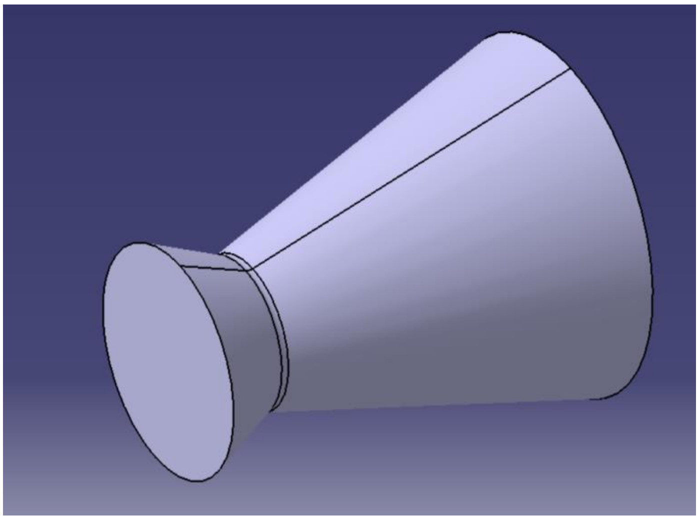


Fig 3.4: Nozzle 3-D Model

3.4 MESHING

The model made using the aforementioned dimensions was meshed using ANSYS mesh mode. Once the meshing of the nozzle is complete and the inflation control is set to "Program Controlled," the named selections for the INLET, OUTLET, and WALL are defined, and the meshing is updated. The best mesh is required to avoid numerical diffusion. The goal of measuring the best mesh quality is accomplished by considering a number of metrics, although the skewness is the most important one.

For Fluent, the most essential mesh metrics are Skewness and Aspect Ratio. Poor mesh quality may result in inaccurate results for all or most applications. In all or most uses, For Skewness, it should be less than 0.8 for Hexa, Tri, and Quad. Less than 0.9 will result in an incorrect solution and/or a slow convergence for tetrahedral problems. Tetrahedral shapes require a value of less than 0.9. Aspect Ratio: It should be less than 40, though the flow characteristics will determine exactly what that is.

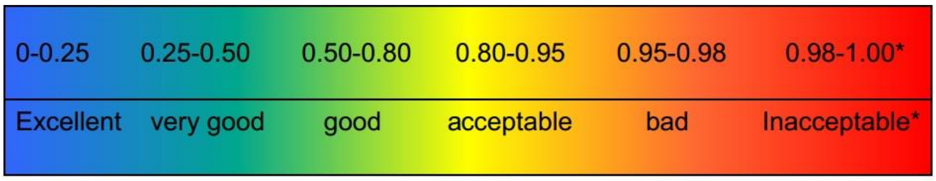


Fig 3.5: Classification of the mesh quality metrics based on skewness

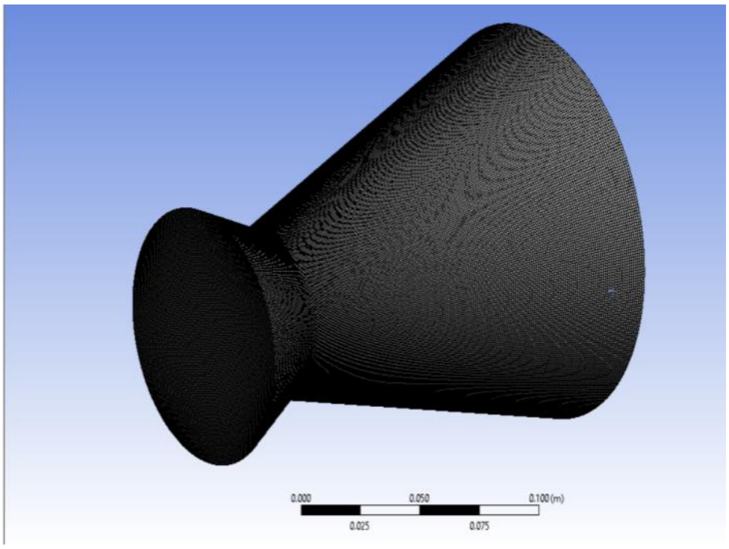
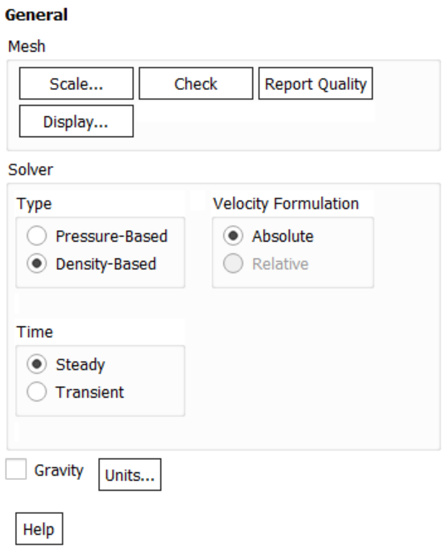


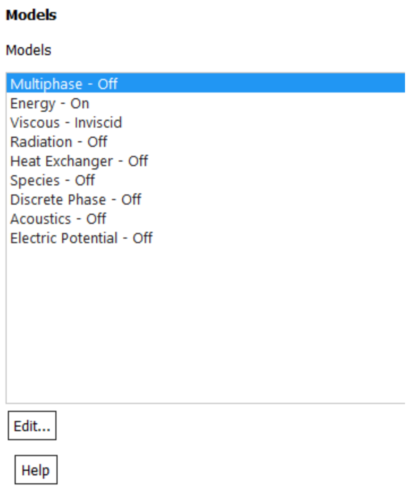
Fig 3.6: Meshing of the Nozzle

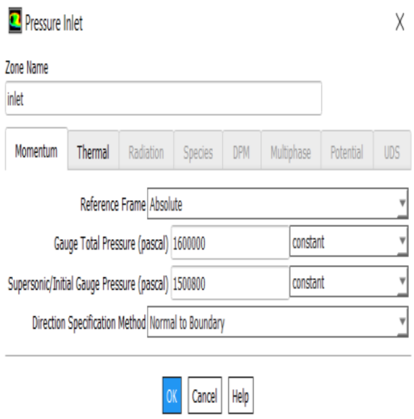
3.5 PRE-PROCESSING

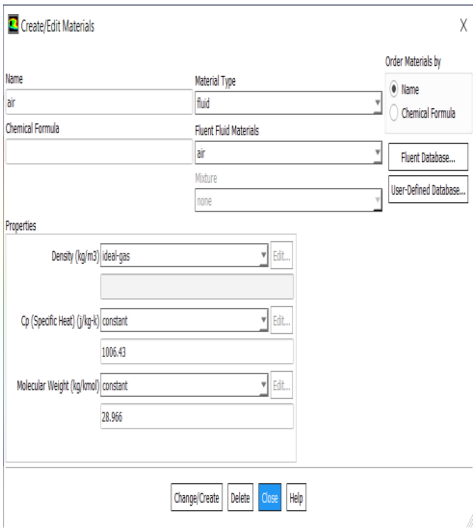
Preprocessing comes after meshing in the CFD process. The meshed model is subjected to the proper boundary conditions during preprocessing. The nozzle was pre-processed using ANSYS FLUENT. Double precision settings were employed.

DETAILS:





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Chemical Formula
Material Type
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Mixture
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Order Materials by
Name
Chemical Formula
Fluent Database...
User-Defined Database...
Properties
Density (kg/m3) ideal-gas
Cp (Specific Heat) (j/kg-k) constant
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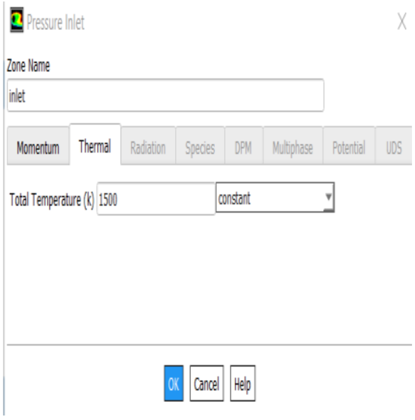
Molecular Weight (kg/kmol) constant
28.966
Change/Create
Delete
Close
Help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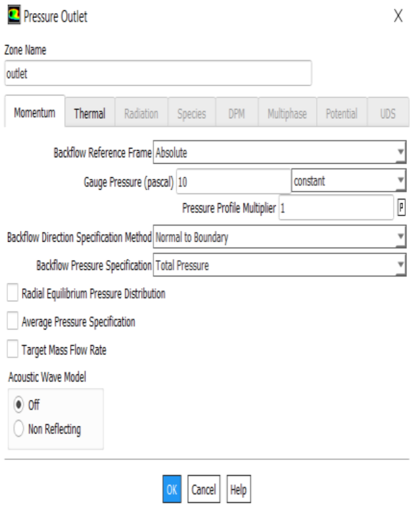
Zone Name
inlet
Momentum
Thermal
Radiation
Species
DPM
Multiphase
Potential
UDS
Total Temperature (k) 1500
constant
OK
Cancel
Help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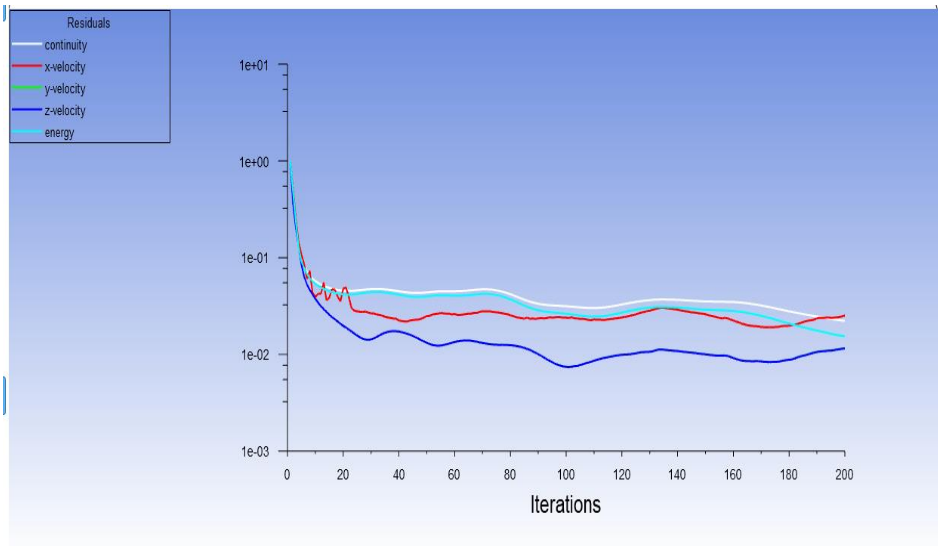
Zone Name
outlet
Momentum
Thermal
Radiation
Species
DPM
Multiphase
Potential
UDS
Backflow Reference Frame Absolute
Gauge Pressure (pascal) 10
constant
Pressure Profile Multiplier 1
Backflow Direction Specification Method Normal to Boundary
Backflow Pressure Specification Total Pressure
Radial Equilibrium Pressure Distribution
Average Pressure Specification
Target Mass Flow Rate
Acoustic Wave Model
Off
Non Reflecting
OK
Cancel
Help


Residuals
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x-velocity
y-velocity
z-velocity
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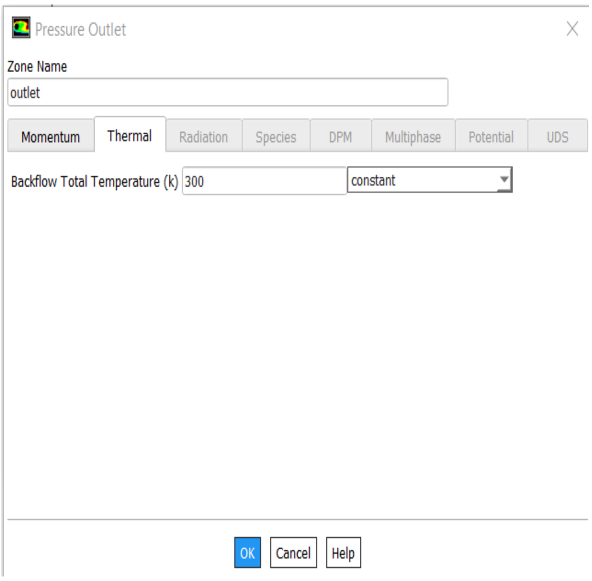
60
80
100
120
140
160
180
200
Iterations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Zone Name
outlet
Momentum
Thermal
Radiation
Species
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Multiphase
Potential
UDS
Backflow Total Temperature (k)
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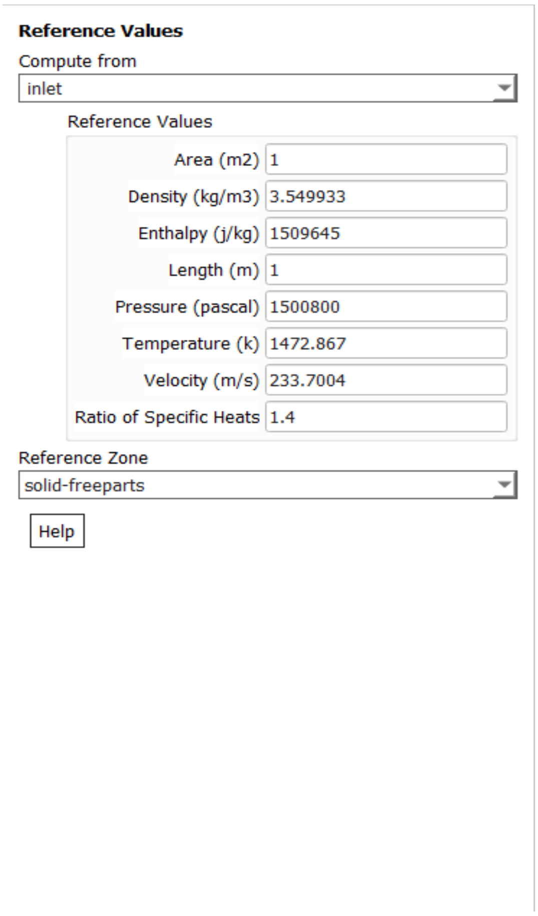
constant
OK
Cancel
Help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inlet
Reference Values
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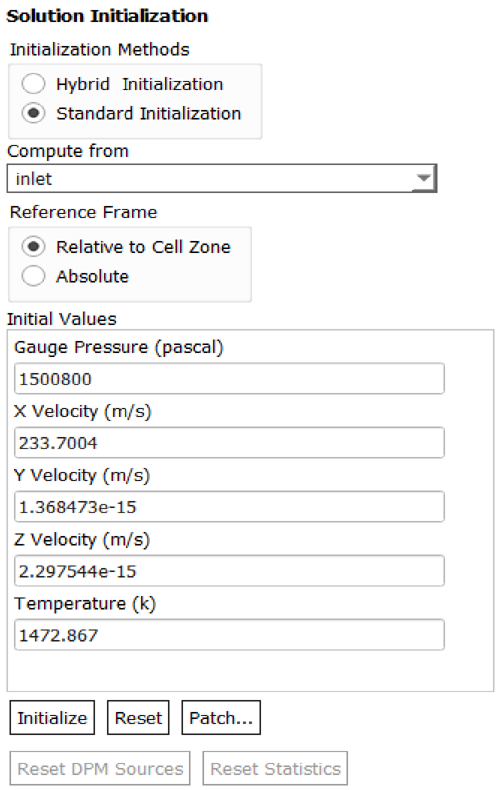
Enthalpy (j/kg) 1509645
Length (m) 1
Pressure (pascal) 1500800
Temperature (k) 1472.867
Velocity (m/s) 233.7004
Ratio of Specific Heats 1.4
Reference Zone
solid-freeparts
Help


Solution Initialization
Initialization Methods
Hybrid Initialization
Standard Initialization
Compute from
inlet
Reference Frame
Relative to Cell Zone
Absolute
Initial Values
Gauge Pressure (pascal)
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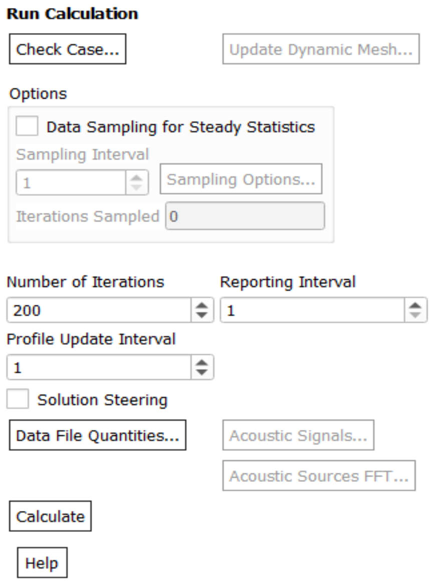
X Velocity (m/s)
233.7004
Y Velocity (m/s)
1.368473e-15
Z Velocity (m/s)
2.297544e-15
Temperature (k)
1472.867
Initialize
Reset
Patch...
Reset DPM Sources
Reset Statistics


Run Calculation
Check Case...
Update Dynamic Mesh...
Options
Data Sampling for Steady Statistics
Sampling Interval
1
Sampling Options...
Iterations Sampled 0
Number of Iterations
Reporting Interval
200
1
Profile Update Interval
1
Solution Steering
Data File Quantities...
Acoustic Signals...
Acoustic Sources FFT...
Calculate
Help

CHAPTER - 4

RESULTS AND DISCUSSION

4.1 INTRODUCTION:

This chapter attempts to analyze and discuss the major project work outcome in the area of rocket nozzles and is summarized. The different cases of nozzle analysis have been carried out. To validate the results, the simulation results are compared to the theoretical approach. For cases 1 to 5, the convergent angle will be 24°, 26°, 28°, 30°, and 32°, respectively.

4.2 CFD RESULTS FOR 26° CONVERGENT ANGLE

Temperature Contour: The temperature is maximum at the inlet and goes on decreasing till the outlet. The magnitude of temperature at the outlet is 779 K.

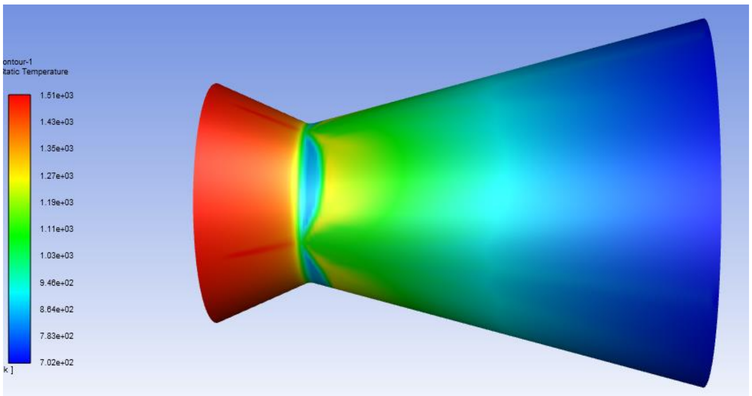


Fig 4.1: Temperature Contour

Pressure Contour: The pressure is maximum at the inlet and goes on decreasing till the outlet. The static pressure at the outlet is 157922.3 Pa. There is sudden decrease in pressure due to shock wave just after the throat section.

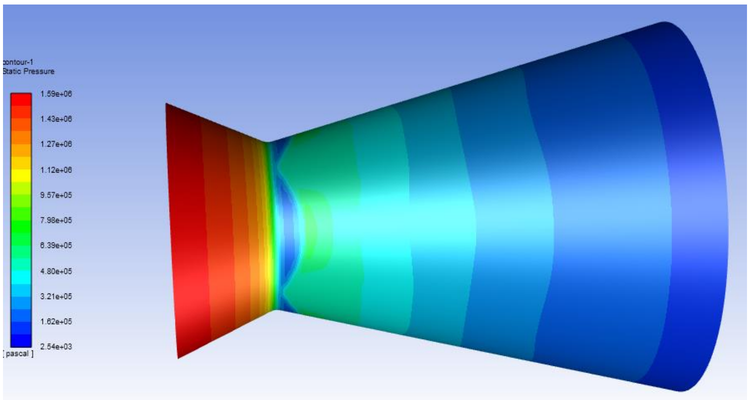


Fig 4.2: Pressure Contour

Mach number Contour:

The velocity is minimum at the inlet and goes on increasing till the nozzle exit. The velocity magnitude is Mach 1 at the throat section of the nozzle. This condition is known as choked flow condition. The Exit Mach is 1.7.

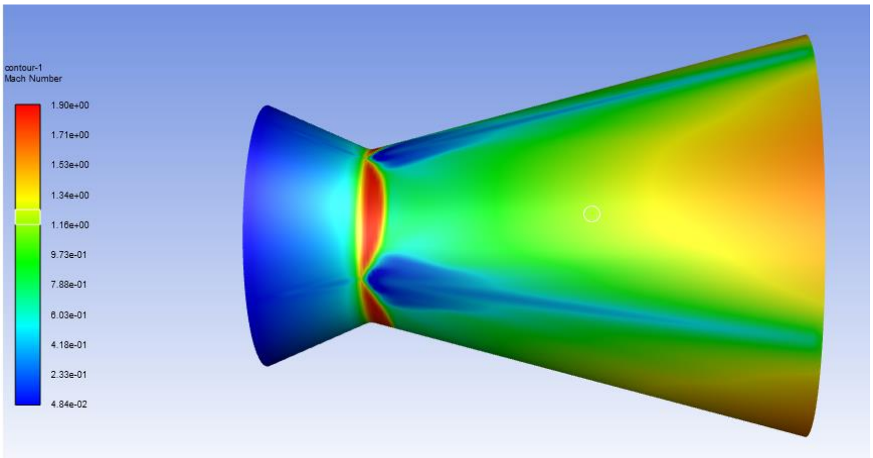


Fig 4.3: Mach number Contour

4.3 THEORETICAL RESULTS FOR 26° CONVERGENT ANGLE:

1. EXIT MACH:

M_e=V/a=558/331=1.68

M_e=1.68

2. EXIT TEMPERATURE:

$(T_e/T_t)=[1+((\gamma-1)/2)M_e^2]^{-1}$

$T_e=1200*[1+((1.4-1)/2)*(1.68)^2]^{-1}$

T_e=767K

3. EXIT PRESSURE:

$(P_e/P_t)=[1+((\gamma-1)/2)M_e^2]^{-(\gamma/\gamma-1)}$

$P_e=7.9*10^5*[1+((1.4-1)/2)*(1.68)^2]^{-(1.4/1.4-1)}$

P_e=164942.29Pa

4. THRUST:

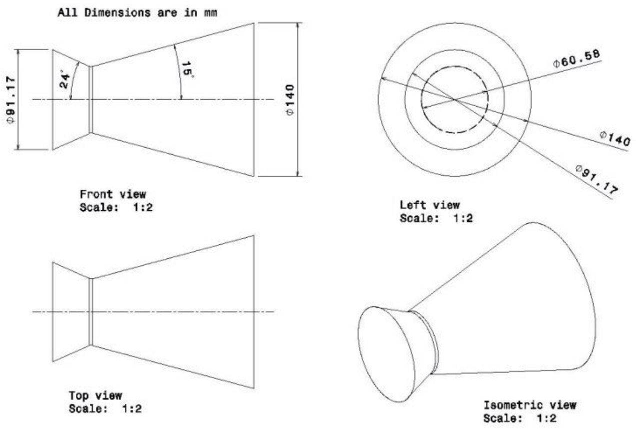
$F=\dot{m}V_e+(P_e-P_o)A_e$

F=(9.1*959)+(164942.29-0)*0.015392

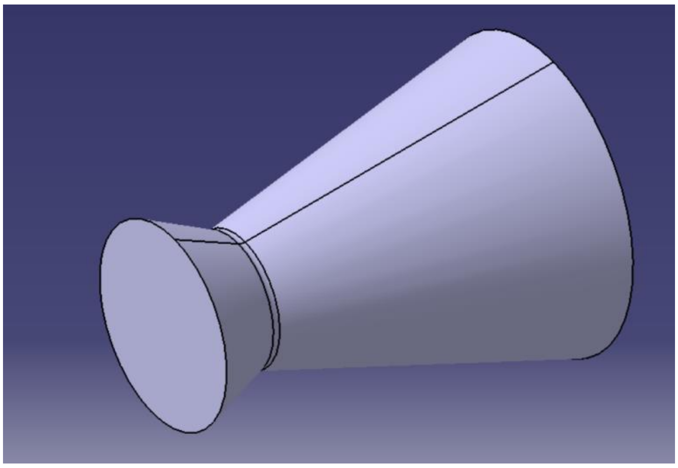
F=11565.69N

4.4 CASE-1 CONVERGENT ANGLE 24°:

NOZZLE DIMENSIONS:



3-D GEOMETRY:



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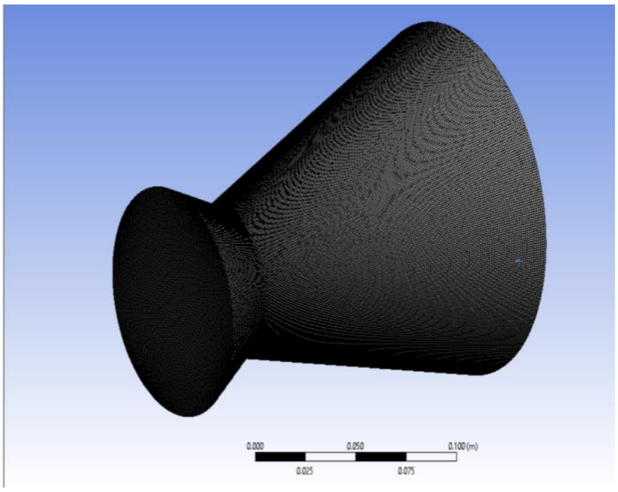

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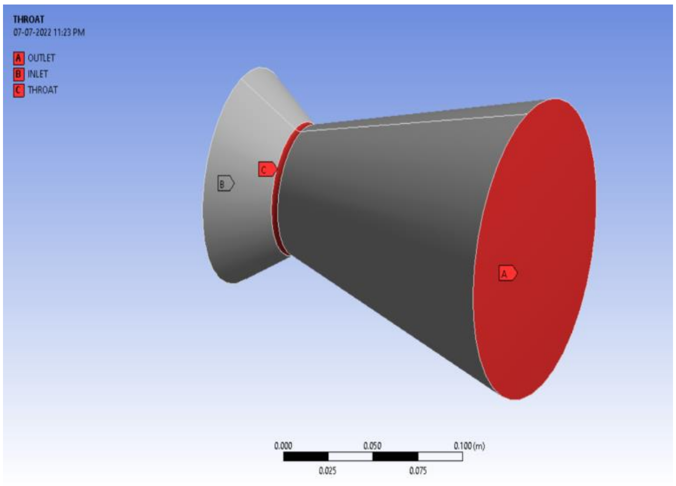
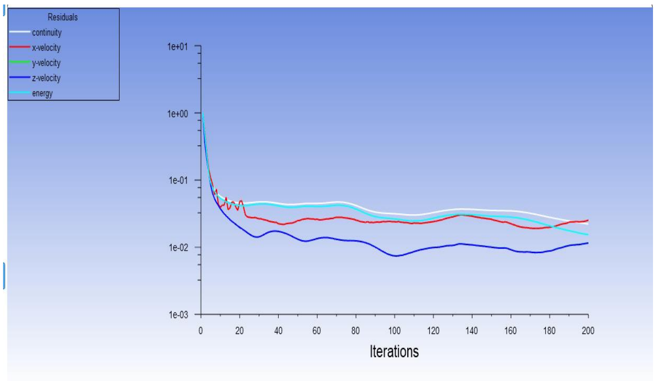
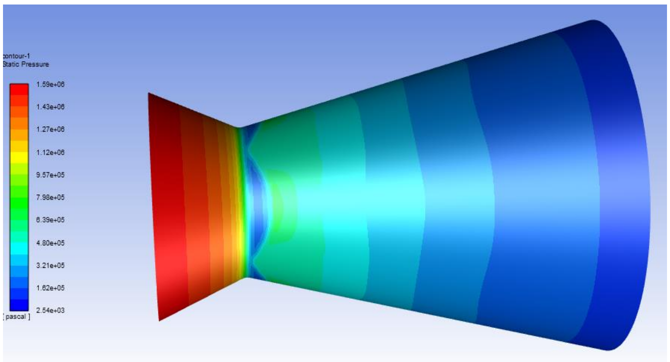


RESIDUALS:



PRESSURE CONTOUR:



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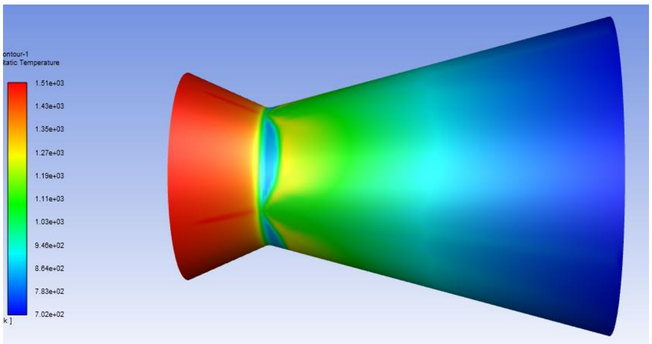

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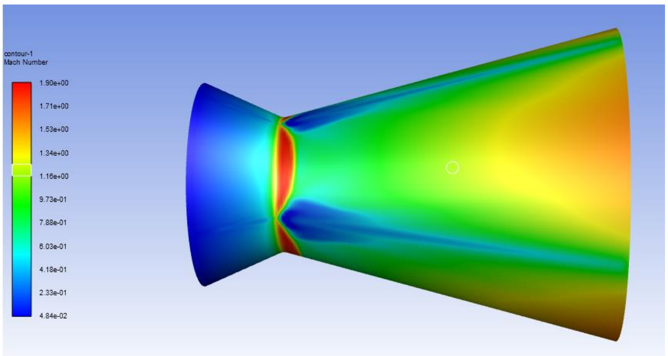

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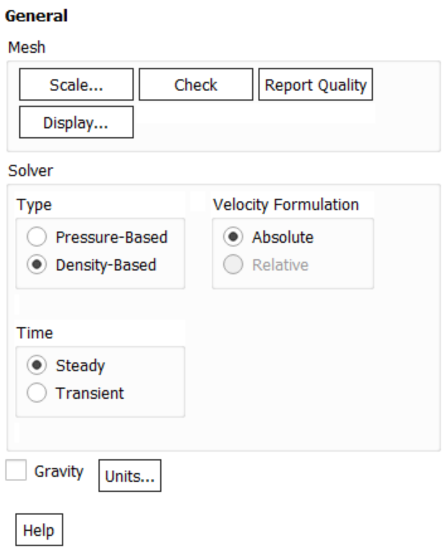
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Display...
Solver
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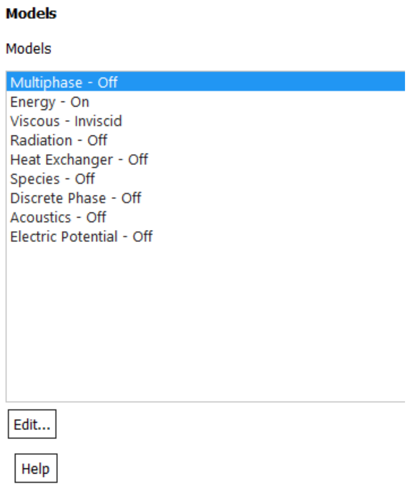
Density-Based
Velocity Formulation
Absolute
Relative
Time
Steady
Transient
Gravity
Units...
Help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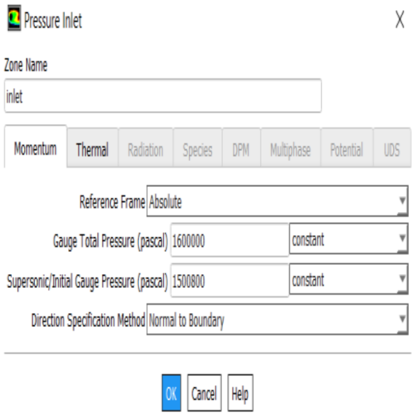
Viscous - Inviscid
Radiation - Off
Heat Exchanger - Off
Species - Off
Discrete Phase - Off
Acoustics - Off
Electric Potential - Off
Edit...
Help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Zone Name
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Momentum
Thermal
Radiation
Species
DPM
Multiphase
Potential
UDS
Reference Frame Absolute
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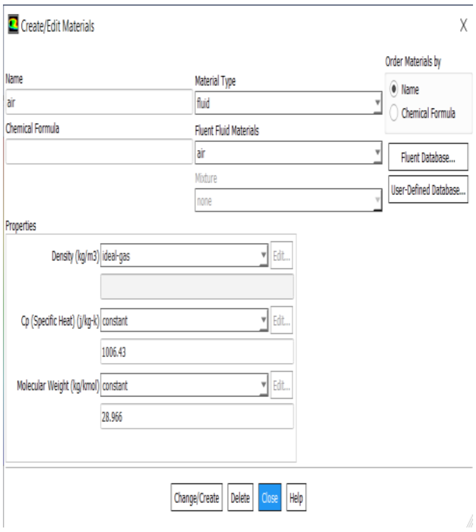
Supersonic/Initial Gauge Pressure (pascal) 1500800 constant
Direction Specification Method Normal to Boundary
OK
Cancel
Help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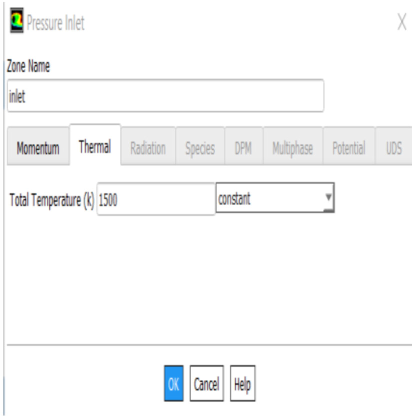
Material Type
fluid
Order Materials by
Name
Chemical Formula
Chemical Formula
Fluent Fluid Materials
air
Fluent Database...
Mixture
none
User-Defined Database...
Properties
Density (kg/m3) ideal-gas
Cp (Specific Heat) (j/kg-k) constant
1006.43
Molecular Weight (kg/kmol) constant
28.966
Change/Create
Delete
Close
Help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Multiphase
Potential
UDS
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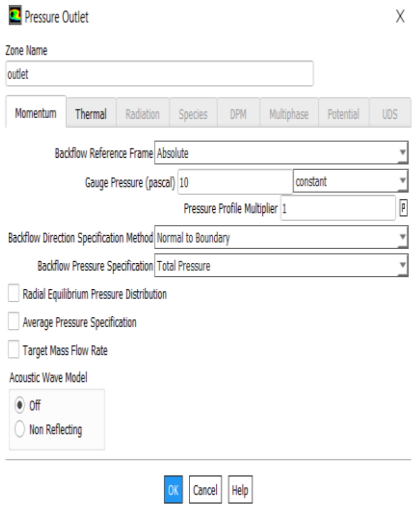
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outlet
Momentum
Thermal
Radiation
Species
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Multiphase
Potential
UDS
Backflow Reference Frame Absolute
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Pressure Profile Multiplier 1
Backflow Direction Specification Method Normal to Boundary
Backflow Pressure Specification Total Pressure
Radial Equilibrium Pressure Distribution
Average Pressure Specification
Target Mass Flow Rate
Acoustic Wave Model
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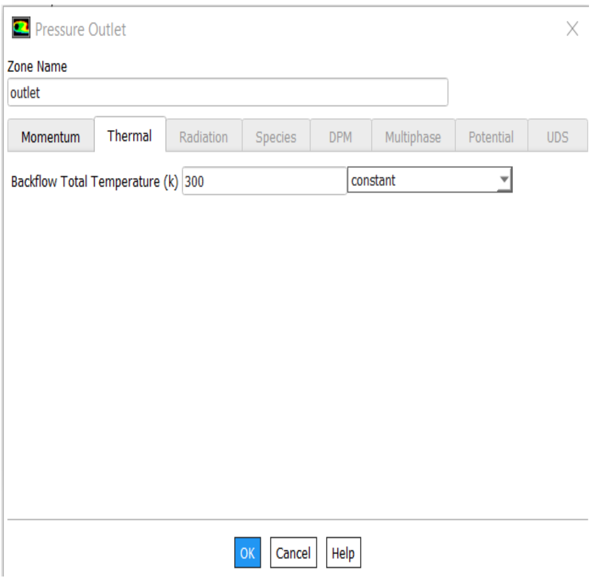
Cancel
Help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Zone Name
outlet
Momentum
Thermal
Radiation
Species
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Multiphase
Potential
UDS
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constant
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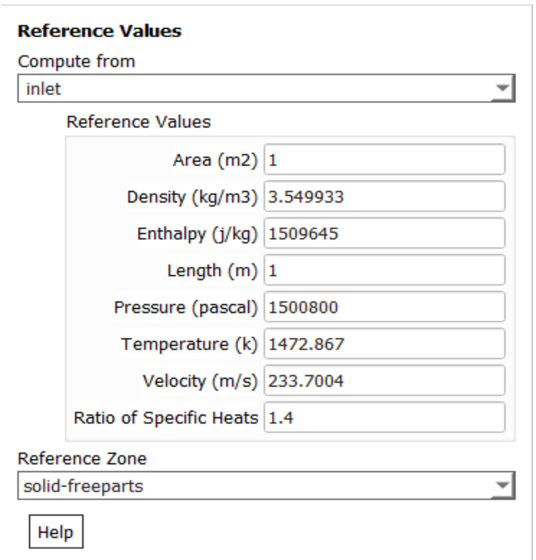
Cancel
Help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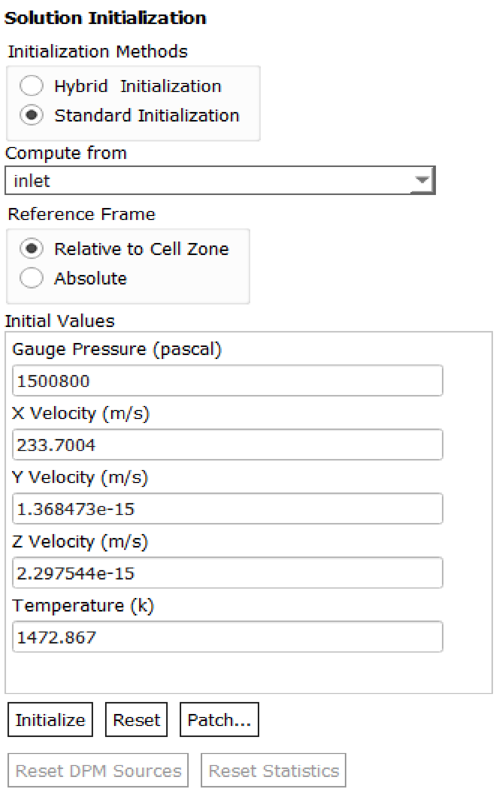
Enthalpy (j/kg) 1509645
Length (m) 1
Pressure (pascal) 1500800
Temperature (k) 1472.867
Velocity (m/s) 233.7004
Ratio of Specific Heats 1.4
Reference Zone
solid-freeparts
Help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Initialization Methods
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Standard Initialization
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Reference Frame
Relative to Cell Zone
Absolute
Initial Values
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X Velocity (m/s)
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Y Velocity (m/s)
1.368473e-15
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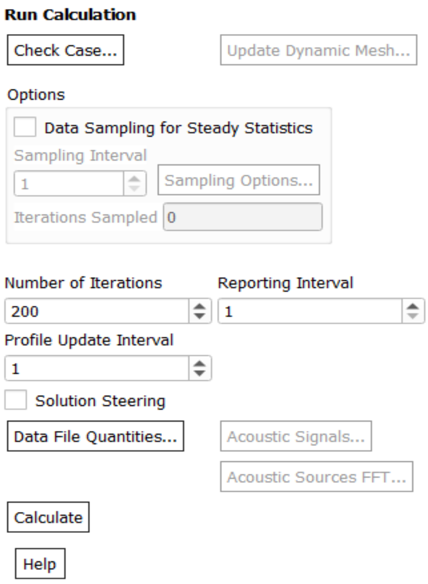
Reset DPM Sources
Reset Statistics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Number of Iterations
Reporting Interval
200
1
Profile Update Interval
1
Solution Steering
Data File Quantities...
Acoustic Signals...
Acoustic Sources FFT...
Calculate
Help

ANALYTICAL METHOD (24°)

1. EXIT MACH:

M_e=V/a=558/331=1.68

M_e=1.68

2. EXIT TEMPERATURE:

$(T_e/T_t)=[1+((\gamma-1)/2)M_e^2]^{-1}$

$T_e=1200*[1+((1.4-1)/2)*(1.68)^2]^{-1}$

T_e=767K

3. EXIT PRESSURE:

$(P_e/P_t)=[1+((\gamma-1)/2)M_e^2]^{-(\gamma/\gamma-1)}$

$P_e=7.9*10^5*[1+((1.4-1)/2)*(1.68)^2]^{-(1.4/1.4-1)}$

P_e=164942.29Pa

4. THRUST:

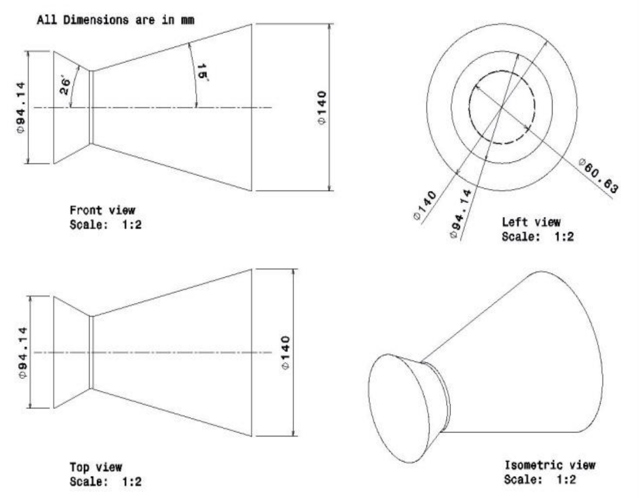
$F=\dot{m}V_e+(P_e-P_o)A_e$

F=(9.1*959)+(164942.29-0)*0.015392

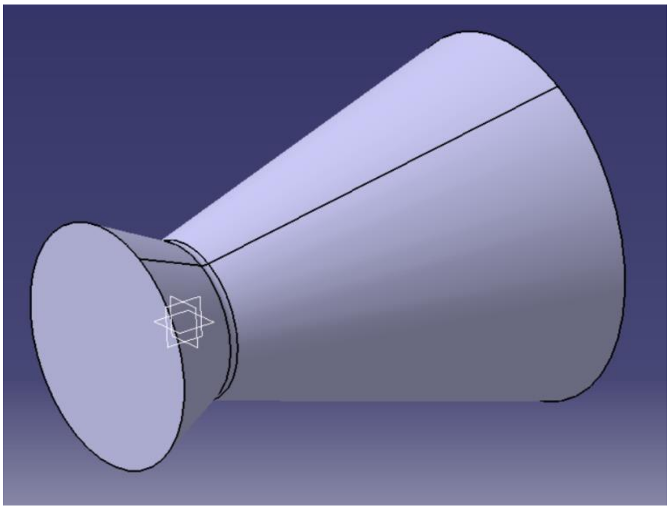
F=11565.69N

4.5 CASE-2 CONVERGENT ANGLE 26°:

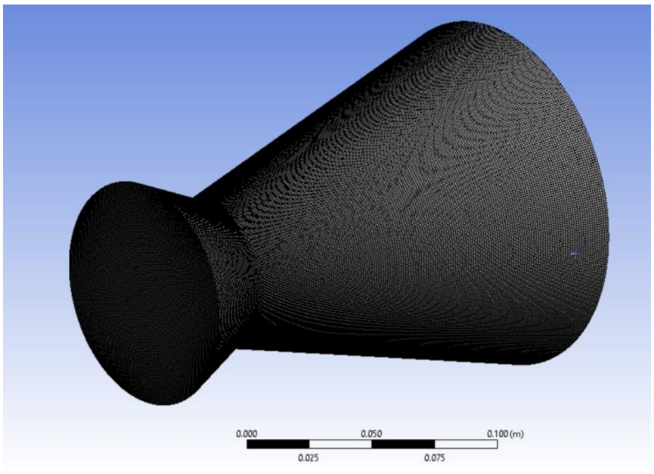
NOZZLE DIMENSIONS:



3-D GEOMETRY:



MESHING:



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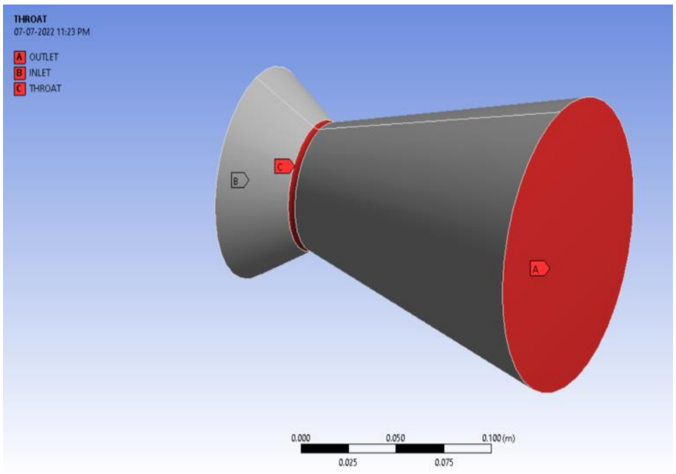

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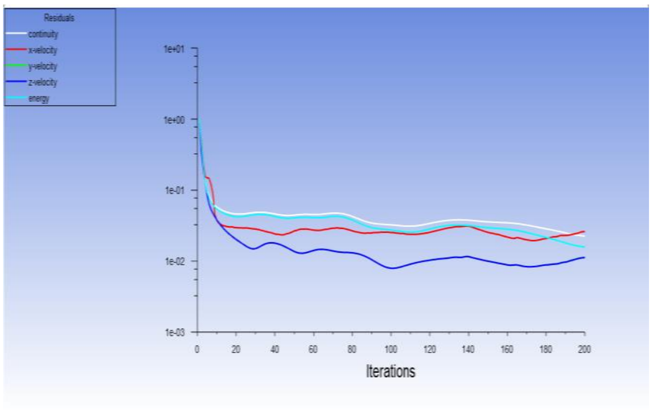

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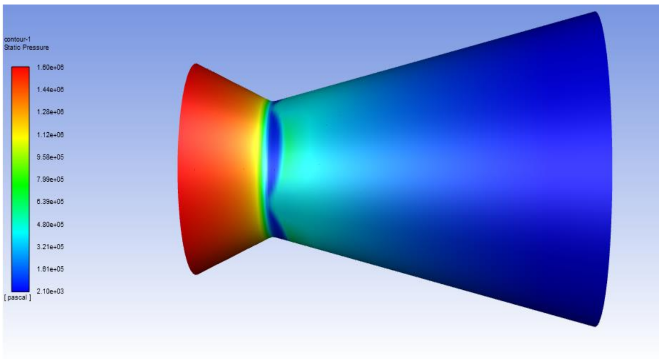
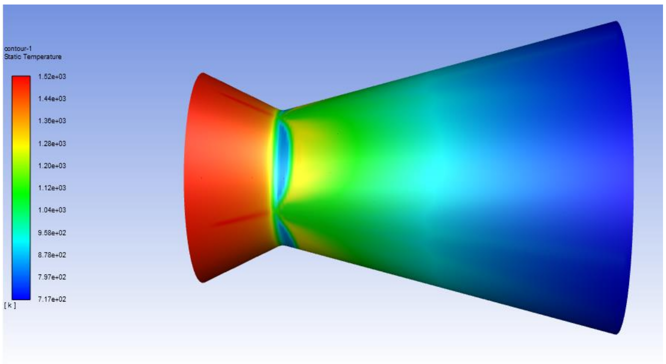
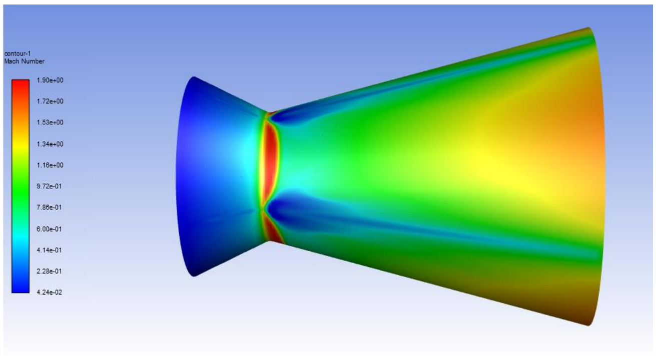


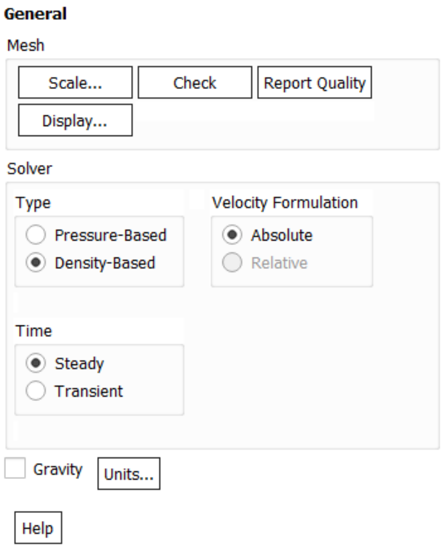
TEMPERATURE CONTOUR:



MACH NUMBER CONTOUR:



DETAILS:



General
Mesh
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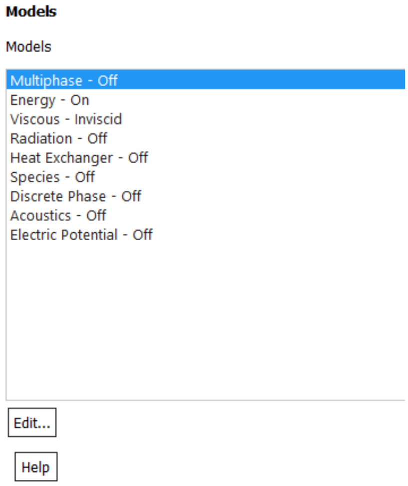
Check
Report Quality
Display...
Solver
Type
Pressure-Based
Density-Based
Velocity Formulation
Absolute
Relative
Time
Steady
Transient
Gravity
Units...
Help



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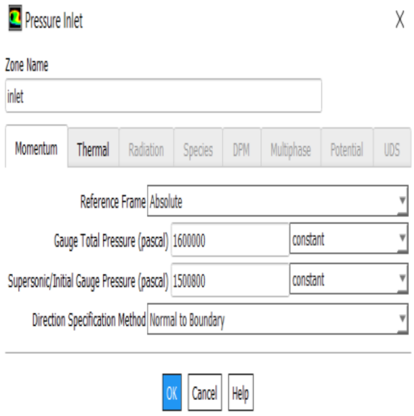
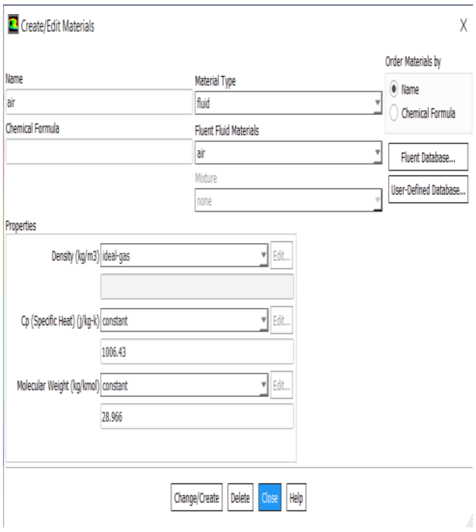
Energy - On
Viscous - Inviscid
Radiation - Off
Heat Exchanger - Off
Species - Off
Discrete Phase - Off
Acoustics - Off
Electric Potential - Off
Edit...
Help



Pressure Inlet
Zone Name
inlet
Momentum
Thermal
Radiation
Species
DPM
Multiphase
Potential
UDS
Reference Frame Absolute
Gauge Total Pressure (pascal) 1600000 constant
Supersonic/Initial Gauge Pressure (pascal) 1500800 constant
Direction Specification Method Normal to Boundary
OK
Cancel
Help



Create/Edit Materials
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Chemical Formula
Material Type
fluid
Fluent Fluid Materials
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Mixture
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Order Materials by
Name
Chemical Formula
Fluent Database...
User-Defined Database...
Properties
Density (kg/m3) ideal-gas
Cp (Specific Heat) (j/kg-k) constant
1006.43
Molecular Weight (kg/kmol) constant
28.966
Change/Create
Delete
Close
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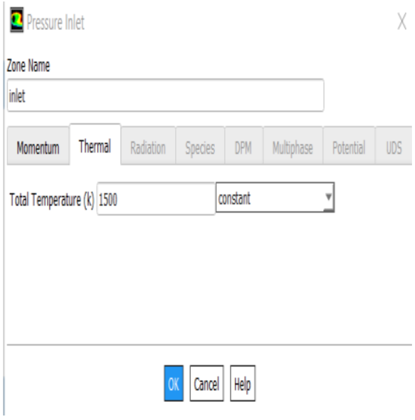
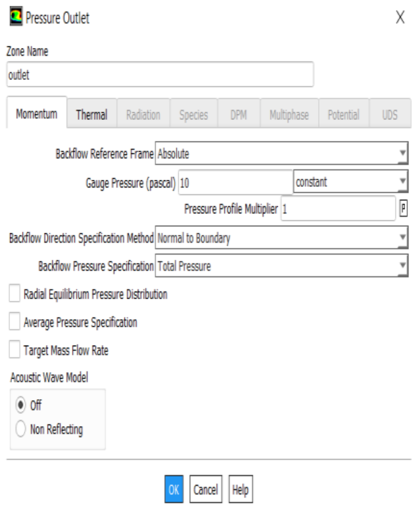
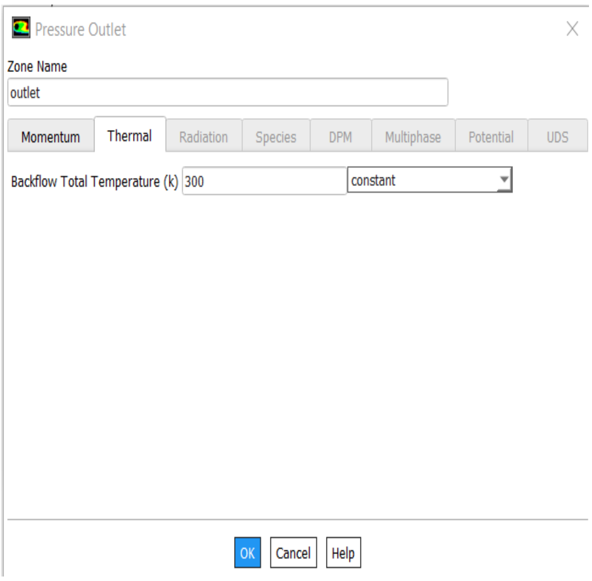
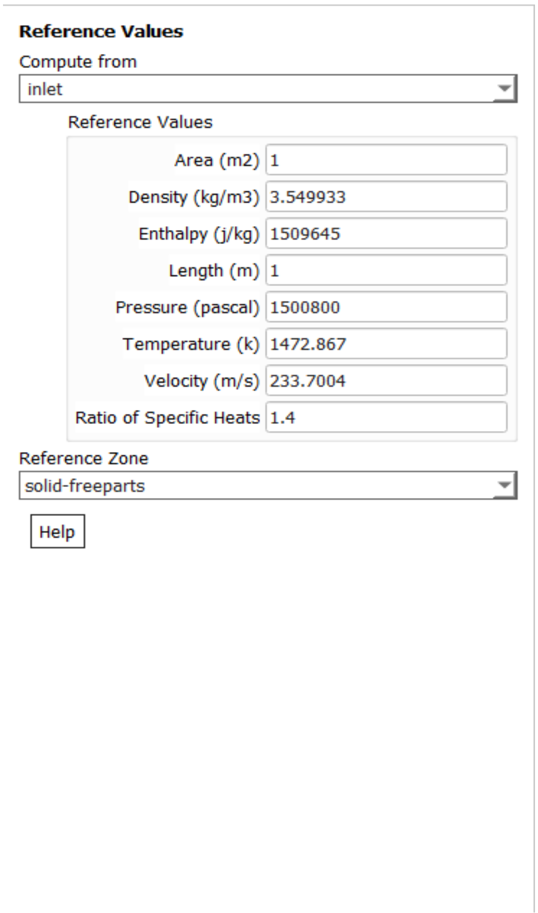


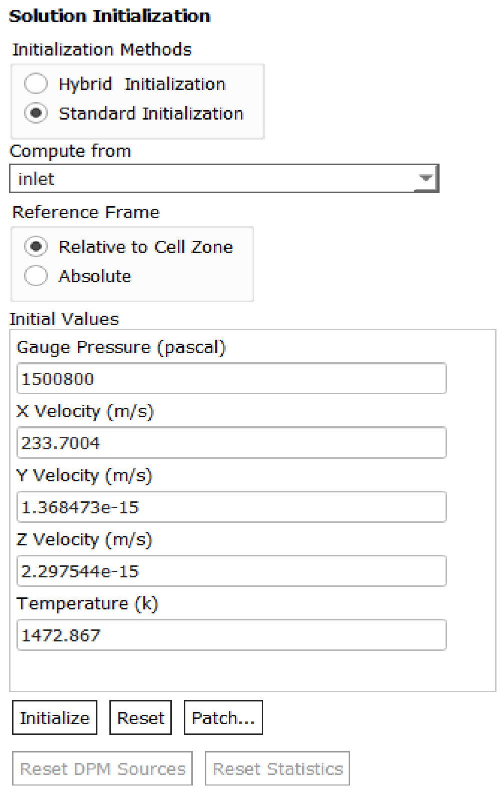
Pressure Inlet
Zone Name
inlet
Momentum
Thermal
Radiation
Species
DPM
Multiphase
Potential
UDS
Total Temperature (k) 1500 constant
OK
Cancel
Help

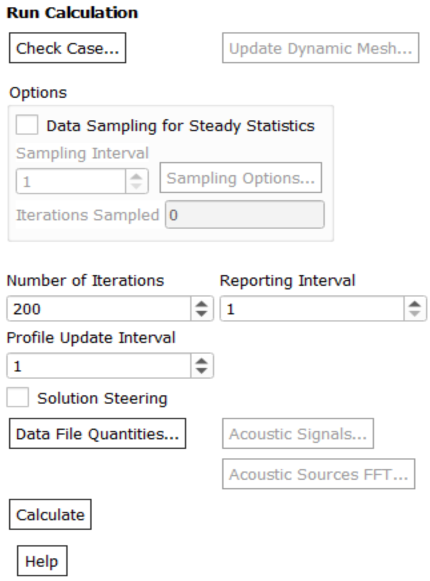


Pressure Outlet
Zone Name
outlet
Momentum
Thermal
Radiation
Species
DPM
Multiphase
Potential
UDS
Backflow Reference Frame Absolute
Gauge Pressure (pascal) 10 constant
Pressure Profile Multiplier 1
Backflow Direction Specification Method Normal to Boundary
Backflow Pressure Specification Total Pressure
Radial Equilibrium Pressure Distribution
Average Pressure Specification
Target Mass Flow Rate
Acoustic Wave Model
Off
Non Reflecting
OK
Cancel
Help


Pressure Outlet
Zone Name
outlet
Momentum
Thermal
Radiation
Species
DPM
Multiphase
Potential
UDS
Backflow Total Temperature (k) 300
constant
OK
Cancel
Help


Reference Values
Compute from
inlet
Reference Values
Area (m2) 1
Density (kg/m3) 3.549933
Enthalpy (j/kg) 1509645
Length (m) 1
Pressure (pascal) 1500800
Temperature (k) 1472.867
Velocity (m/s) 233.7004
Ratio of Specific Heats 1.4
Reference Zone
solid-freeparts
Help


Solution Initialization
Initialization Methods
Hybrid Initialization
Standard Initialization
Compute from
inlet
Reference Frame
Relative to Cell Zone
Absolute
Initial Values
Gauge Pressure (pascal)
1500800
X Velocity (m/s)
233.7004
Y Velocity (m/s)
1.368473e-15
Z Velocity (m/s)
2.297544e-15
Temperature (k)
1472.867
Initialize
Reset
Patch...
Reset DPM Sources
Reset Statistics


Run Calculation
Check Case...
Update Dynamic Mesh...
Options
Data Sampling for Steady Statistics
Sampling Interval
1
Sampling Options...
Iterations Sampled 0
Number of Iterations
Reporting Interval
200
1
Profile Update Interval
1
Solution Steering
Data File Quantities...
Acoustic Signals...
Acoustic Sources FFT...
Calculate
Help

ANALYTICAL METHOD (26°)

1. EXIT MACH:

M_e=V/a=554.69/331=1.67

M_e=1.67

2. EXIT TEMPERATURE:

$(T_e/T_t)=[1+((\gamma-1)/2)M_e^2]^{-1}$

$T_e=1200*[1+((1.4-1)/2)*(1.67)^2]^{-1}$

T_e=770.32K

3. EXIT PRESSURE:

$(P_e/P_t)=[1+((\gamma-1)/2)M_e^2]^{-(\gamma/\gamma-1)}$

$P_e=7.95*10^5*[1+((1.4-1)/2)*(1.67)^2]^{-(1.4/1.4-1)}$

P_e=165986.29Pa

4. THRUST:

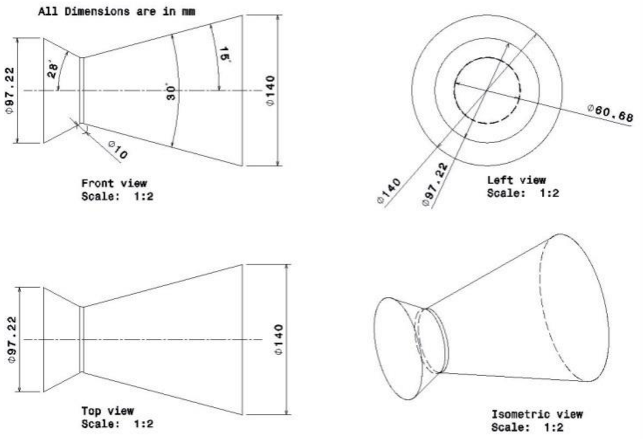
$F=\dot{m}V_e+(P_e-P_o)A_e$

F=(9.7*960)+(165986.29 -0)*0.015392

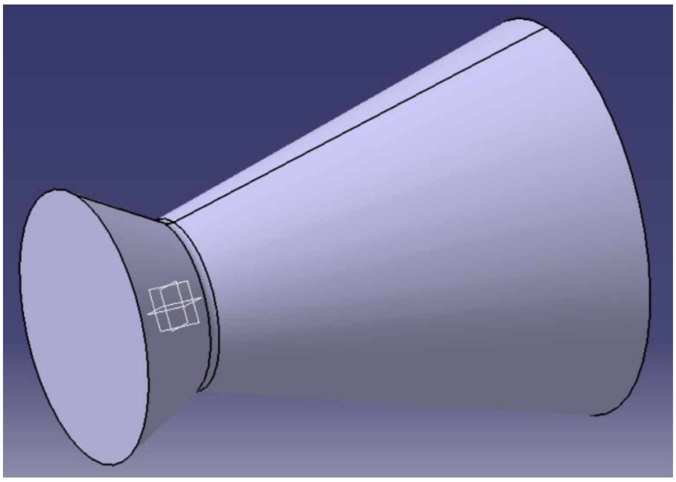
F=11867N

4.6 CASE-3 CONVERGENT ANGLE 28°:

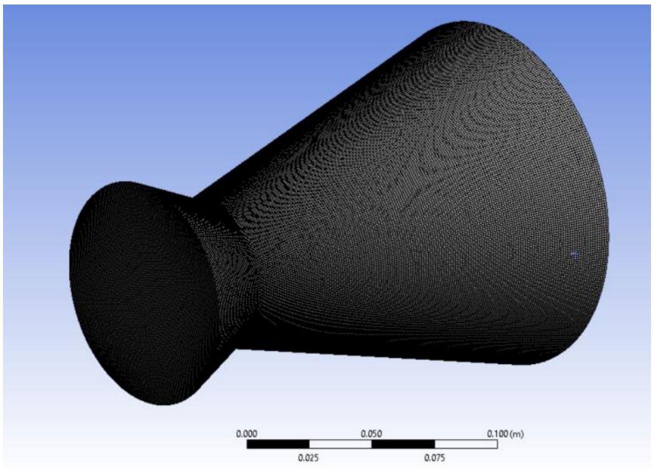
NOZZLE DIMENSIONS:



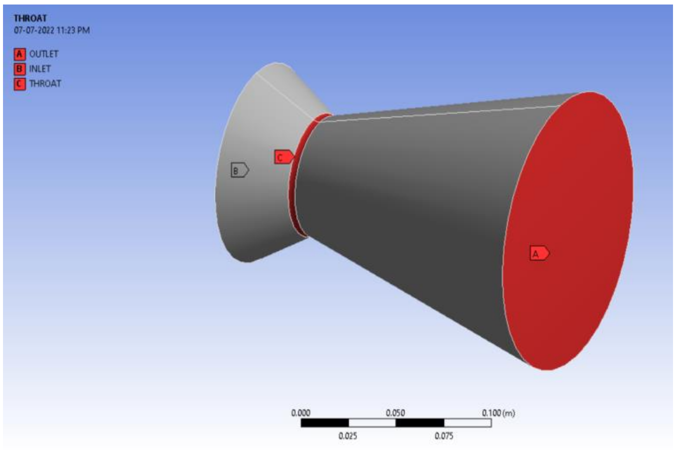
3-D GEOMETRY:



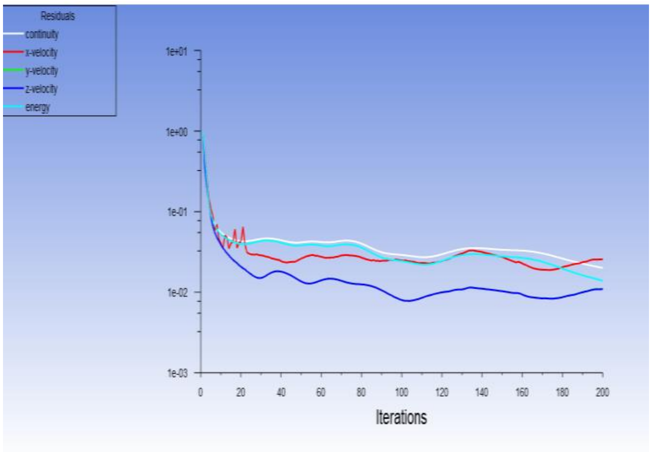
MESHING:



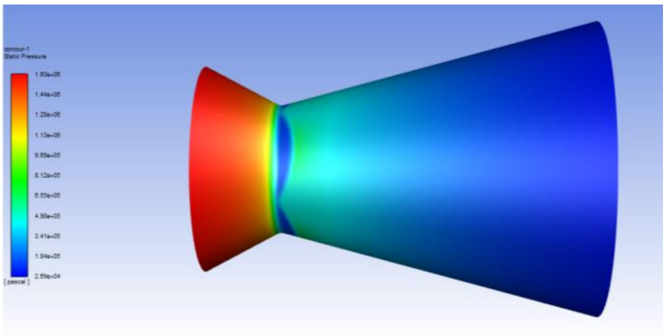
NAMED SELECTION:



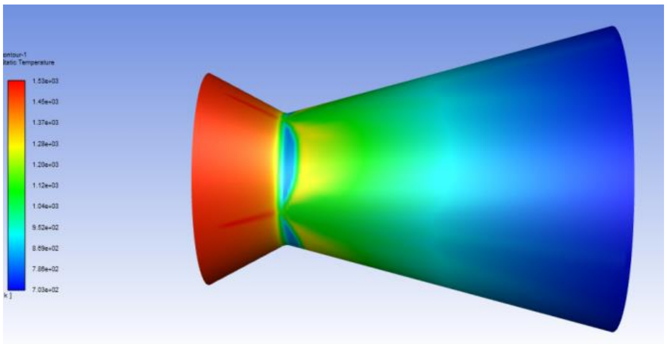
RESIDUALS:



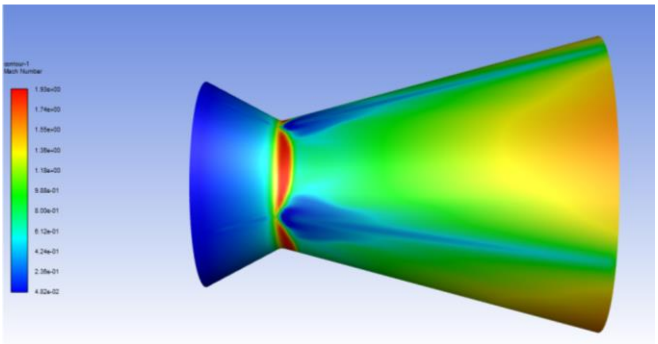
PRESSURE CONTOUR:



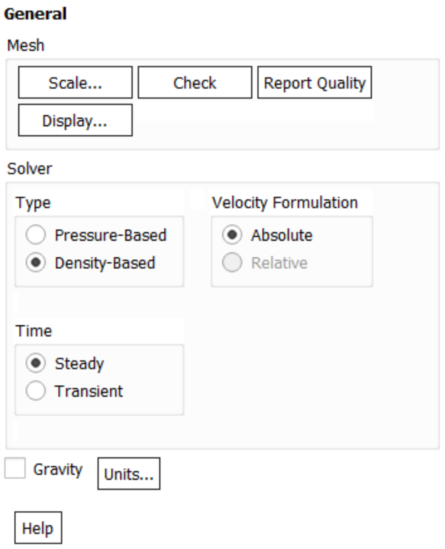
TEMPERATURE CONTOUR:

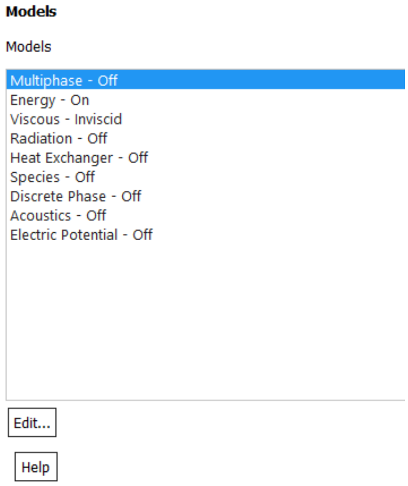


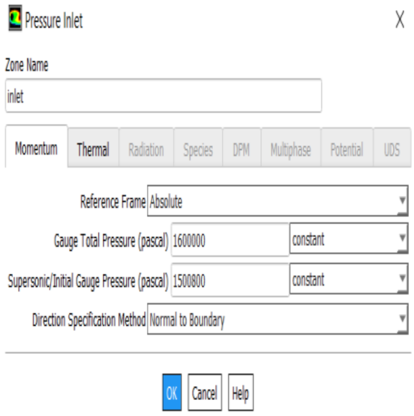
MACH NUMBER CONTOUR:

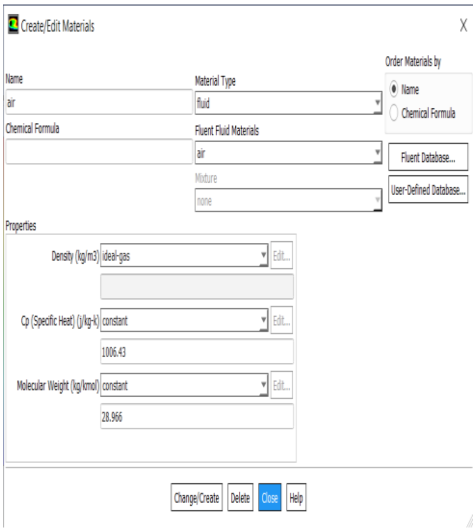


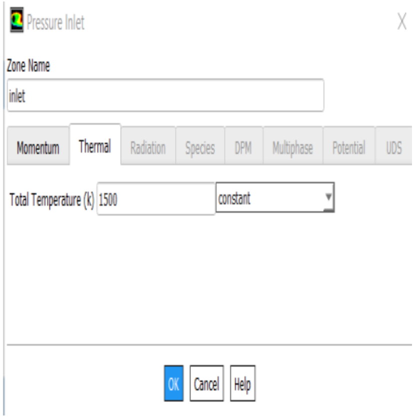
DETAILS:

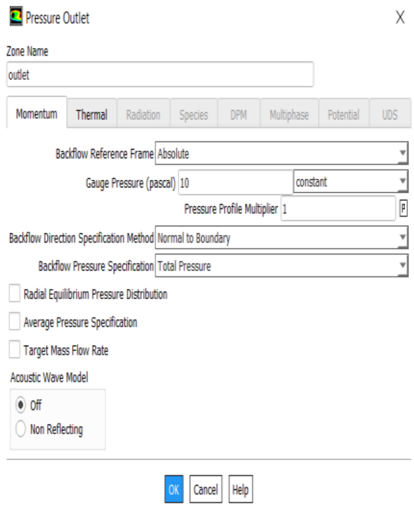

General
Mesh
Scale...
Check
Report Quality
Display...
Solver
Type
Pressure-Based
Density-Based
Velocity Formulation
Absolute
Relative
Time
Steady
Transient
Gravity
Units...
Help

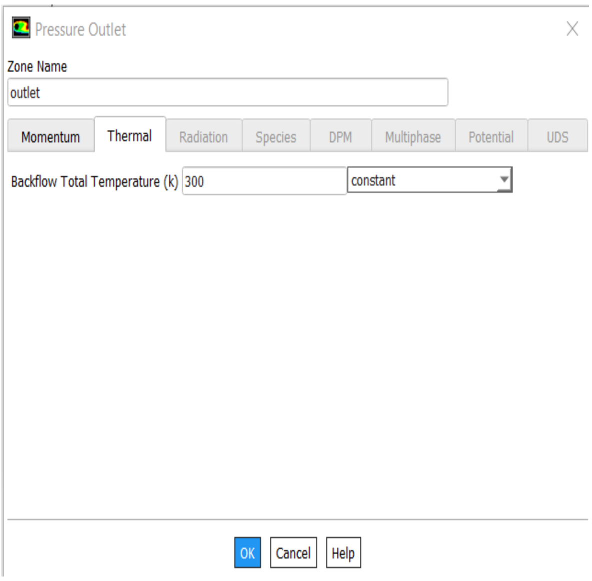

Models
Models
Multiphase - Off
Energy - On
Viscous - Inviscid
Radiation - Off
Heat Exchanger - Off
Species - Off
Discrete Phase - Off
Acoustics - Off
Electric Potential - Off
Edit...
Help

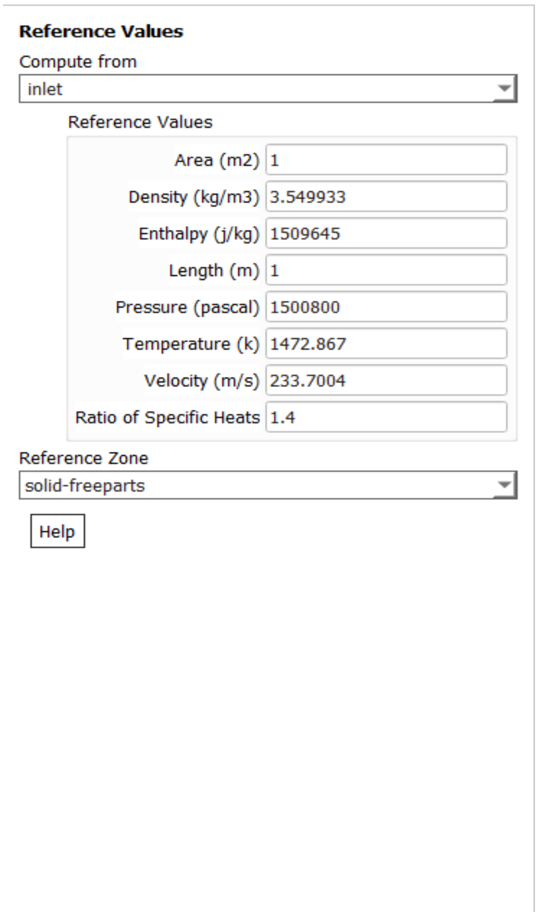

Pressure Inlet
Zone Name
inlet
Momentum
Thermal
Radiation
Species
DPM
Multiphase
Potential
UDS
Reference Frame Absolute
Gauge Total Pressure (pascal) 1600000 constant
Supersonic/Initial Gauge Pressure (pascal) 1500800 constant
Direction Specification Method Normal to Boundary
OK
Cancel
Help

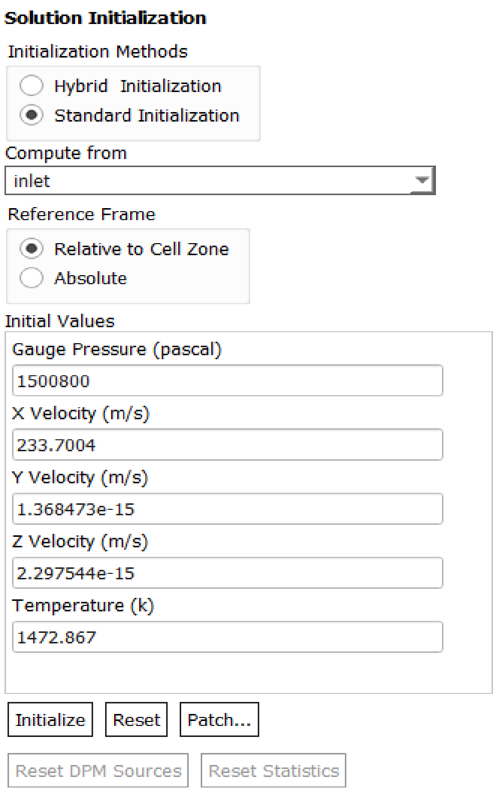

Create/Edit Materials
Name
air
Chemical Formula
Material Type
fluid
Fluent Fluid Materials
air
Mixture
none
Order Materials by
Name
Chemical Formula
Fluent Database...
User-Defined Database...
Properties
Density (kg/m3) ideal-gas
Cp (Specific Heat) (j/kg-k) constant
1006.43
Molecular Weight (kg/kmol) constant
28.966
Change/Create
Delete
Close
Help

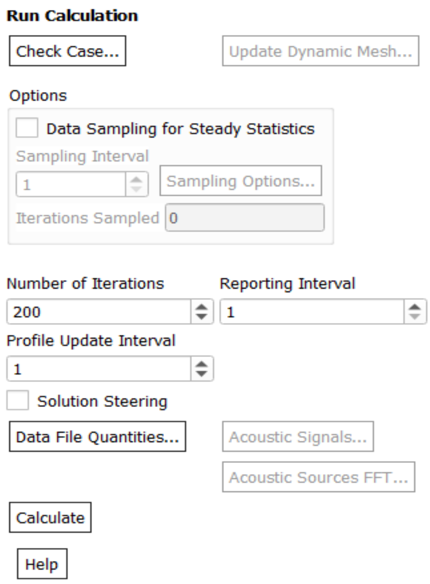

Pressure Inlet
Zone Name
inlet
Momentum
Thermal
Radiation
Species
DPM
Multiphase
Potential
UDS
Total Temperature (k) 1500 constant
OK
Cancel
Help


Pressure Outlet
Zone Name
outlet
Momentum
Thermal
Radiation
Species
DPM
Multiphase
Potential
UDS
Backflow Reference Frame Absolute
Gauge Pressure (pascal) 10 constant
Pressure Profile Multiplier 1
Backflow Direction Specification Method Normal to Boundary
Backflow Pressure Specification Total Pressure
Radial Equilibrium Pressure Distribution
Average Pressure Specification
Target Mass Flow Rate
Acoustic Wave Model
Off
Non Reflecting
OK
Cancel
Help


Pressure Outlet
Zone Name
outlet
Momentum
Thermal
Radiation
Species
DPM
Multiphase
Potential
UDS
Backflow Total Temperature (k) 300
constant
OK
Cancel
Help


Reference Values
Compute from
inlet
Reference Values
Area (m2) 1
Density (kg/m3) 3.549933
Enthalpy (j/kg) 1509645
Length (m) 1
Pressure (pascal) 1500800
Temperature (k) 1472.867
Velocity (m/s) 233.7004
Ratio of Specific Heats 1.4
Reference Zone
solid-freeparts
Help


Solution Initialization
Initialization Methods
Hybrid Initialization
Standard Initialization
Compute from
inlet
Reference Frame
Relative to Cell Zone
Absolute
Initial Values
Gauge Pressure (pascal)
1500800
X Velocity (m/s)
233.7004
Y Velocity (m/s)
1.368473e-15
Z Velocity (m/s)
2.297544e-15
Temperature (k)
1472.867
Initialize
Reset
Patch...
Reset DPM Sources
Reset Statistics


Run Calculation
Check Case...
Update Dynamic Mesh...
Options
Data Sampling for Steady Statistics
Sampling Interval
1
Sampling Options...
Iterations Sampled 0
Number of Iterations
200
Reporting Interval
1
Profile Update Interval
1
Solution Steering
Data File Quantities...
Acoustic Signals...
Acoustic Sources FFT...
Calculate
Help

ANALYTICAL METHOD (28°)

1. EXIT MACH:

$M_e=V/a=563.54/331=1.70$

$M_e=1.70$

2. EXIT TEMPERATURE:

$(T_e/T_t)=[1+((\gamma-1)/2)M_e^2]^{-1}$

$T_e=1250*[1+((1.4-1)/2)*(1.70)^2]^{-1}$

$T_e=792.125K$

3. EXIT PRESSURE:

$(P_e/P_t)=[1+((\gamma-1)/2)M_e^2]^{-(\gamma/\gamma-1)}$

$P_e=848000*[1+((1.4-1)/2)*(1.7)^2]^{-(1.4/1.4-1)}$

$P_e=171799.28Pa$

4. THRUST:

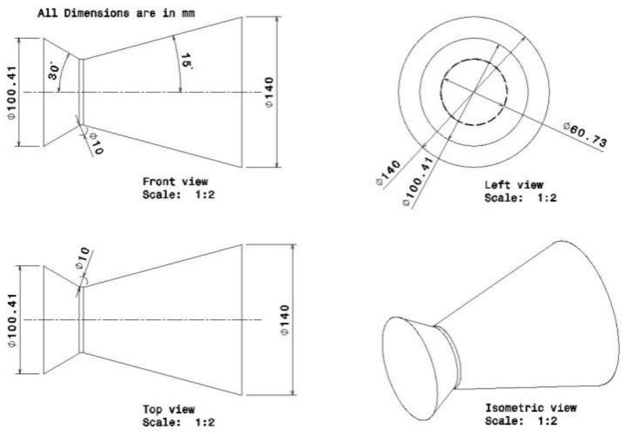
$F=\dot{m}V_e+(P_e-P_o)A_e$

$F=(9.13*779)+(171799.28-0)*0.015392$

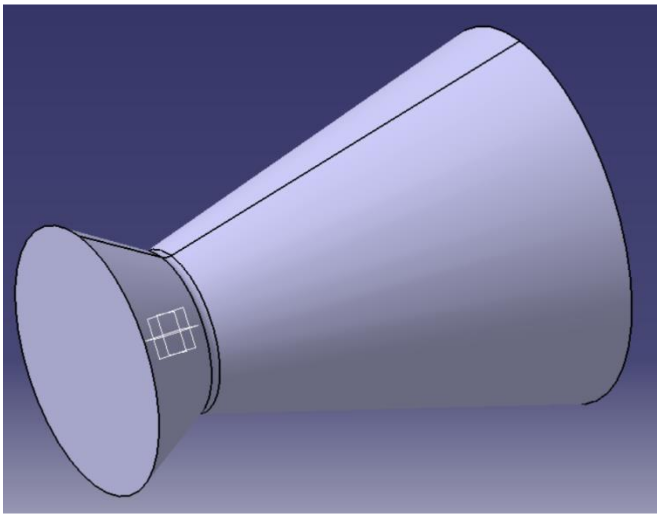
$F=9740.79N$

4.7 CASE-4 CONVERGENT ANGLE 30°:

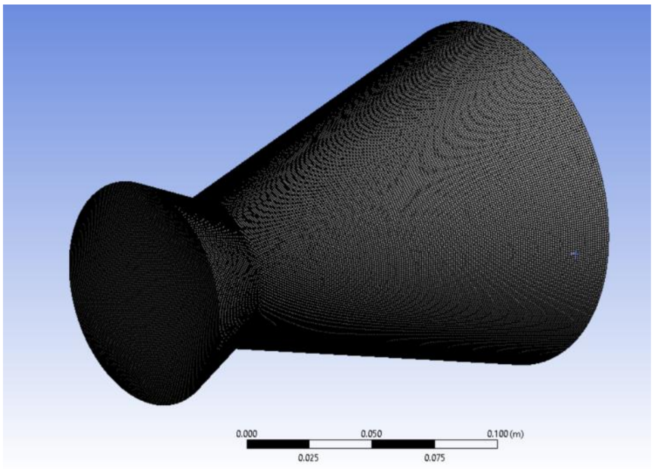
NOZZLE DIMENSIONS:



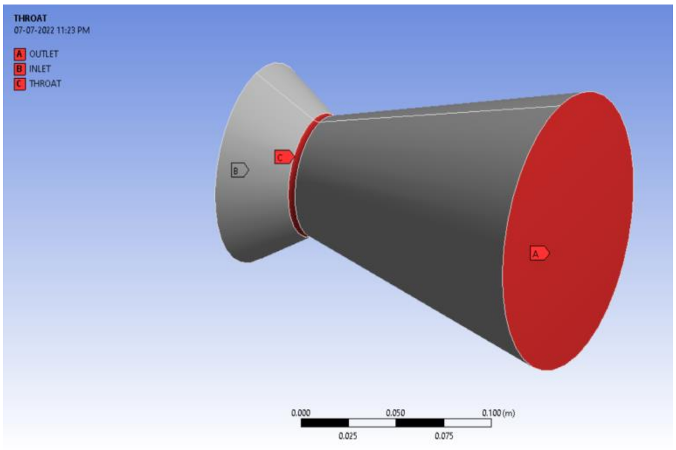
3-D GEOMETRY:



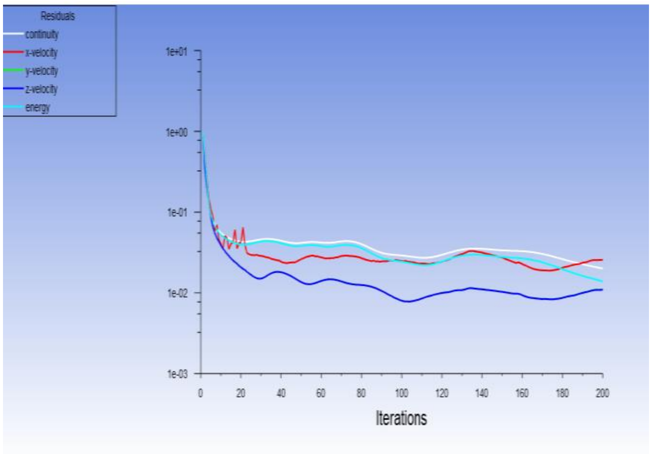
MESHING:



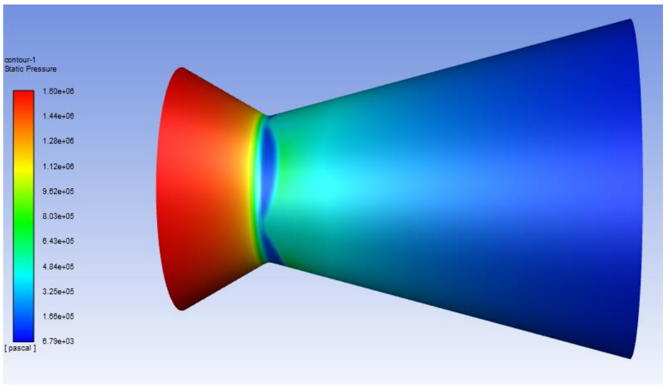
NAMED SELECTION:



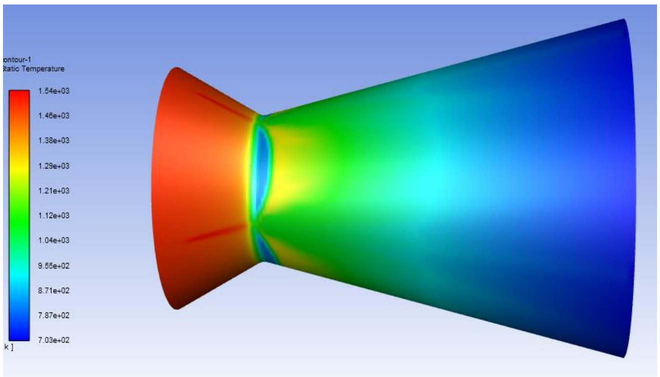
RESIDUALS:



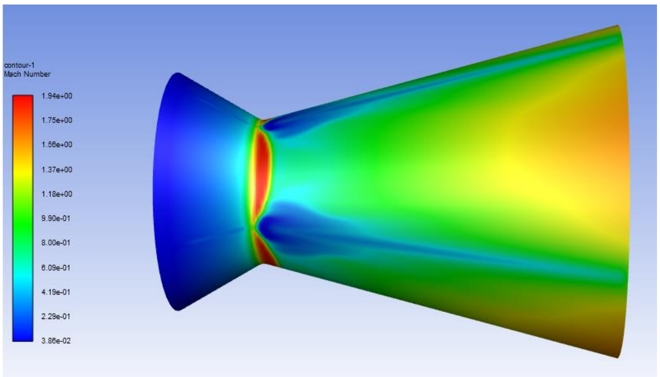
PRESSURE CONTOUR:



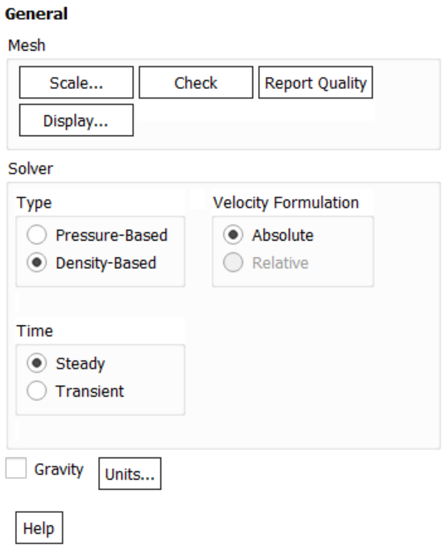
TEMPERATURE CONTOUR:

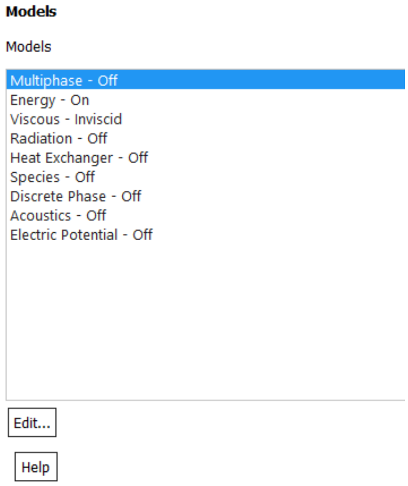


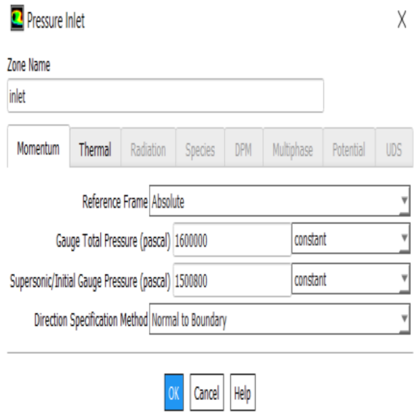
MACH NUMBER CONTOUR:

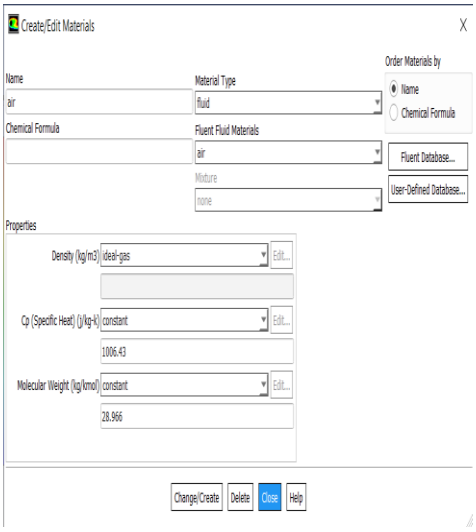


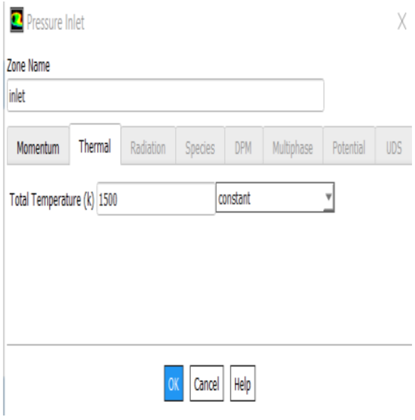
DETAILS:

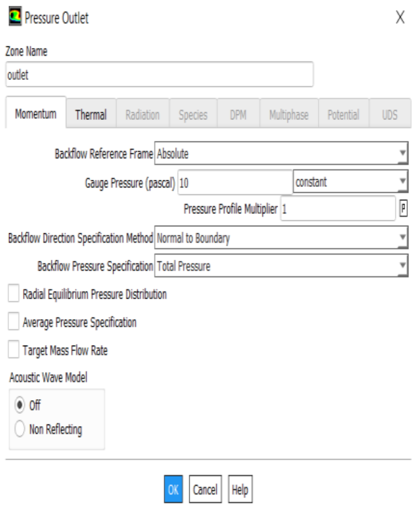

General
Mesh
Scale...
Check
Report Quality
Display...
Solver
Type
Pressure-Based
Density-Based
Velocity Formulation
Absolute
Relative
Time
Steady
Transient
Gravity
Units...
Help

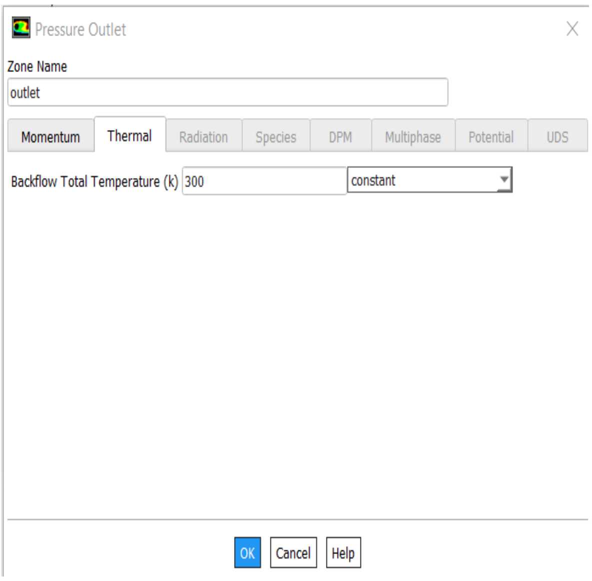

Models
Models
Multiphase - Off
Energy - On
Viscous - Inviscid
Radiation - Off
Heat Exchanger - Off
Species - Off
Discrete Phase - Off
Acoustics - Off
Electric Potential - Off
Edit...
Help

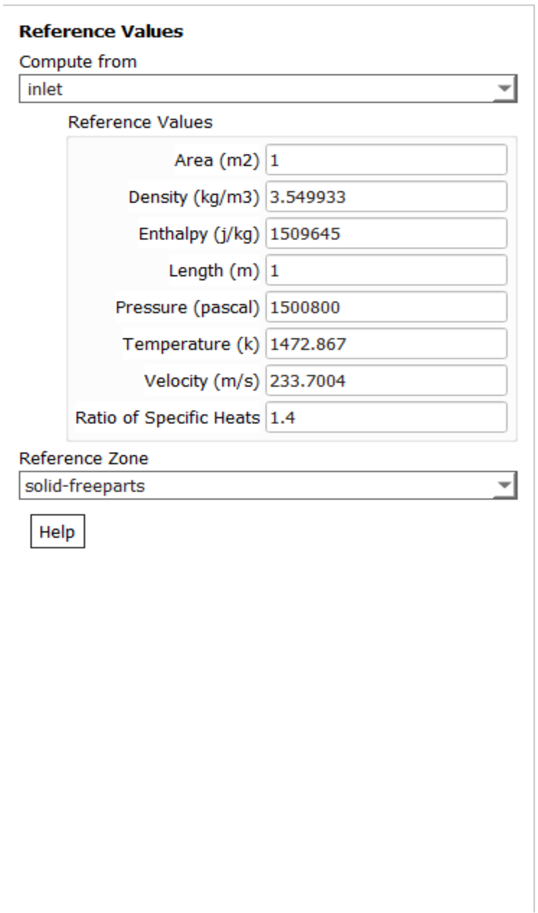

Pressure Inlet
Zone Name
inlet
Momentum
Thermal
Radiation
Species
DPM
Multiphase
Potential
UDS
Reference Frame Absolute
Gauge Total Pressure (pascal) 1600000 constant
Supersonic/Initial Gauge Pressure (pascal) 1500800 constant
Direction Specification Method Normal to Boundary
OK
Cancel
Help

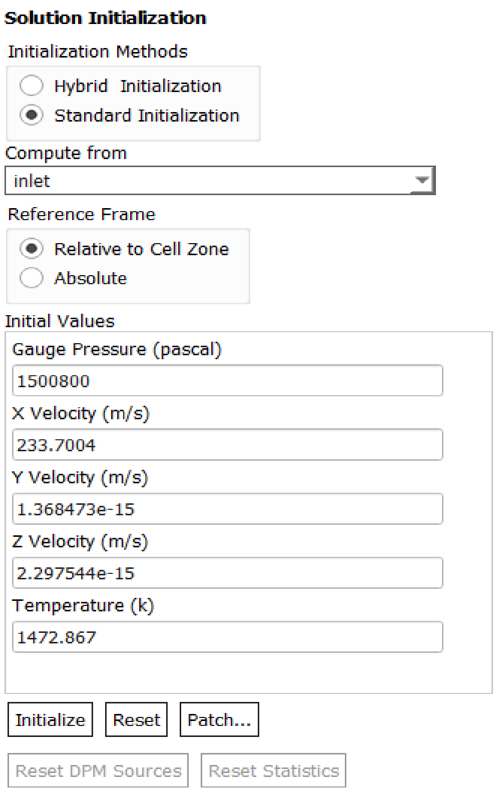

Create/Edit Materials
Name
air
Chemical Formula
Material Type
fluid
Fluent Fluid Materials
air
Mixture
none
Order Materials by
Name
Chemical Formula
Fluent Database...
User-Defined Database...
Properties
Density (kg/m3) ideal-gas
Cp (Specific Heat) (j/kg-k) constant
1006.43
Molecular Weight (kg/kmol) constant
28.966
Change/Create
Delete
Close
Help

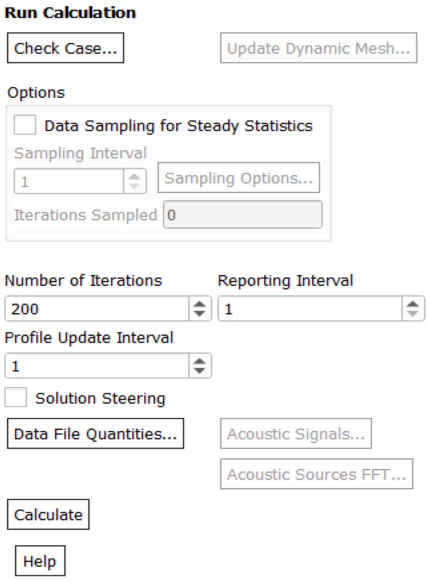

Pressure Inlet
Zone Name
inlet
Momentum
Thermal
Radiation
Species
DPM
Multiphase
Potential
UDS
Total Temperature (k) 1500 constant
OK
Cancel
Help


Pressure Outlet
Zone Name
outlet
Momentum
Thermal
Radiation
Species
DPM
Multiphase
Potential
UDS
Backflow Reference Frame Absolute
Gauge Pressure (pascal) 10 constant
Pressure Profile Multiplier 1
Backflow Direction Specification Method Normal to Boundary
Backflow Pressure Specification Total Pressure
Radial Equilibrium Pressure Distribution
Average Pressure Specification
Target Mass Flow Rate
Acoustic Wave Model
Off
Non Reflecting
OK
Cancel
Help


Pressure Outlet
Zone Name
outlet
Momentum
Thermal
Radiation
Species
DPM
Multiphase
Potential
UDS
Backflow Total Temperature (k) 300
constant
OK
Cancel
Help


Reference Values
Compute from
inlet
Reference Values
Area (m2) 1
Density (kg/m3) 3.549933
Enthalpy (j/kg) 1509645
Length (m) 1
Pressure (pascal) 1500800
Temperature (k) 1472.867
Velocity (m/s) 233.7004
Ratio of Specific Heats 1.4
Reference Zone
solid-freeparts
Help


Solution Initialization
Initialization Methods
Hybrid Initialization
Standard Initialization
Compute from
inlet
Reference Frame
Relative to Cell Zone
Absolute
Initial Values
Gauge Pressure (pascal)
1500800
X Velocity (m/s)
233.7004
Y Velocity (m/s)
1.368473e-15
Z Velocity (m/s)
2.297544e-15
Temperature (k)
1472.867
Initialize
Reset
Patch...
Reset DPM Sources
Reset Statistics


Run Calculation
Check Case...
Update Dynamic Mesh...
Options
Data Sampling for Steady Statistics
Sampling Interval
1
Sampling Options...
Iterations Sampled 0
Number of Iterations
Reporting Interval
200
1
Profile Update Interval
1
Solution Steering
Data File Quantities...
Acoustic Signals...
Acoustic Sources FFT...
Calculate
Help

ANALYTICAL METHOD (30°)

1. EXIT MACH:

M_e=V/a=553/331=1.67

M_e=1.67

2. EXIT TEMPERATURE:

$(T_e/T_t)=[1+((\gamma-1)/2)M_e^2]^{-1}$

$T_e=1299*[1+((1.4-1)/2)*(1.67)^2]^{-1}$

T_e=833.82K

3. EXIT PRESSURE:

$(P_e/P_t)=[1+((\gamma-1)/2)M_e^2]^{-(\gamma/\gamma-1)}$

$P_e=858062*[1+((1.4-1)/2)*(1.67)^2]^{-(1.4/1.4-1)}$

P_e=181864.20Pa

4. THRUST:

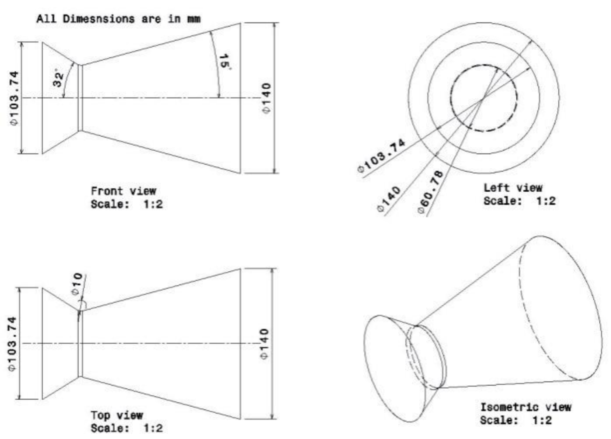
$F=\dot{m}V_e+(P_e-P_o)A_e$

F=(9.14*963)+(181864.20-0)*0.015392

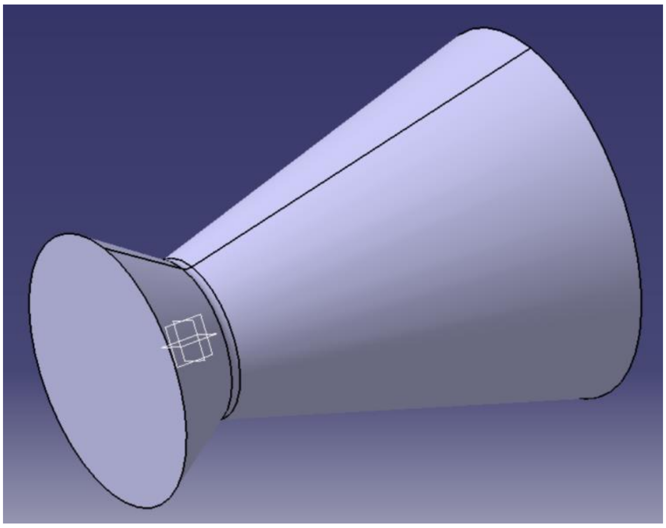
F=11584.3N

4.8 CASE-5 CONVERGENT ANGLE 32°:

NOZZLE DIMENSION:



3-D GEOMETRY:



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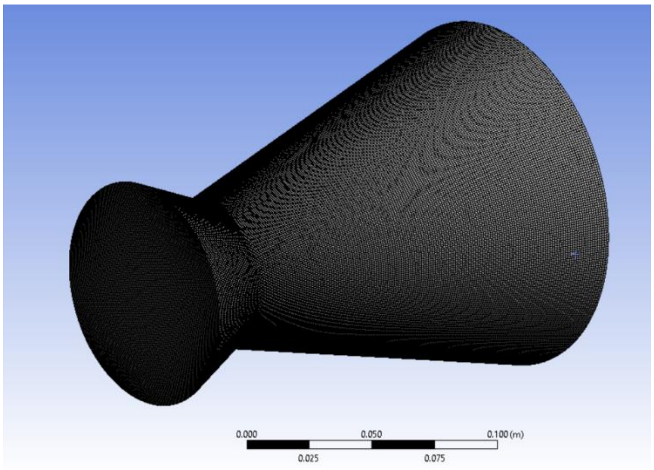
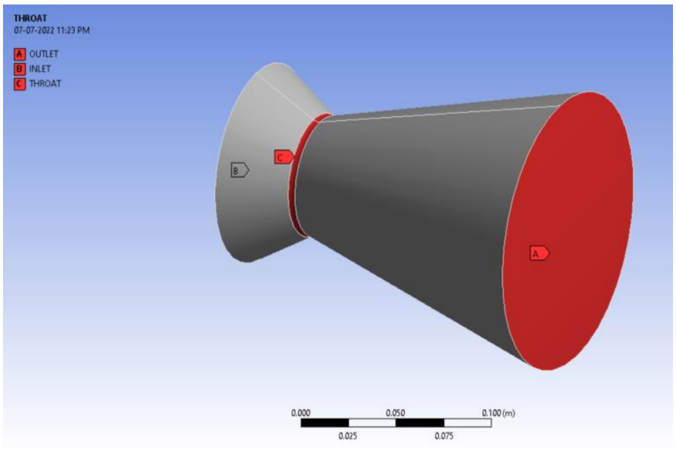
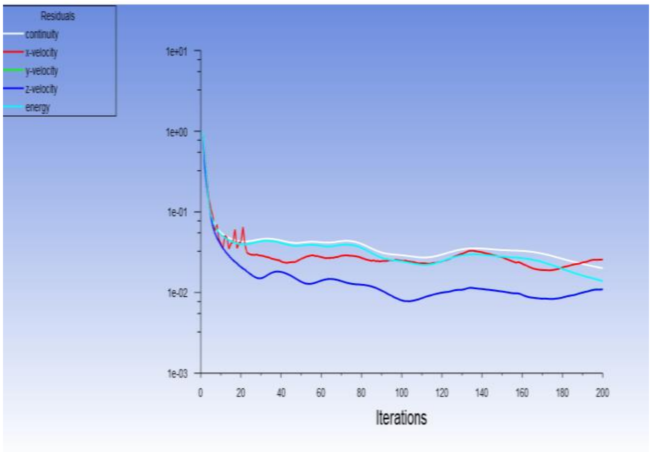


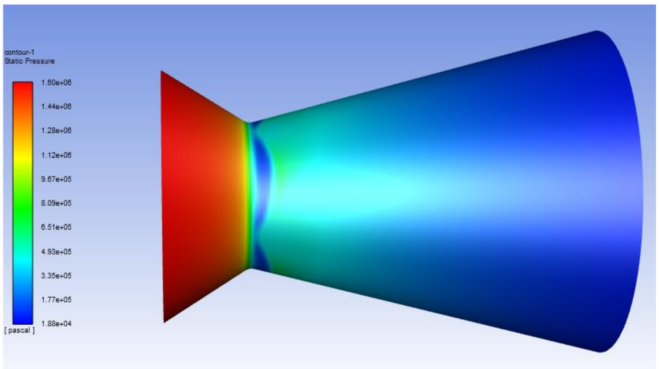
NAMED SELECTION:



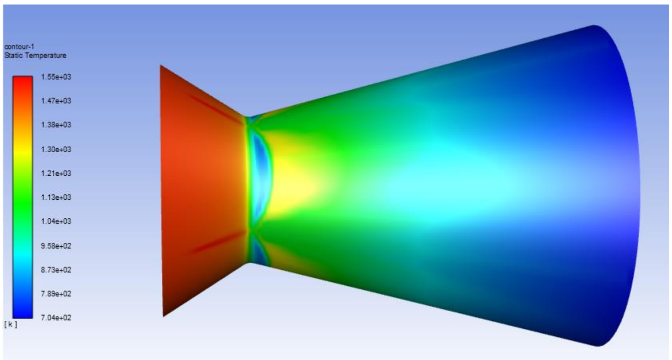
RESIDUALS:



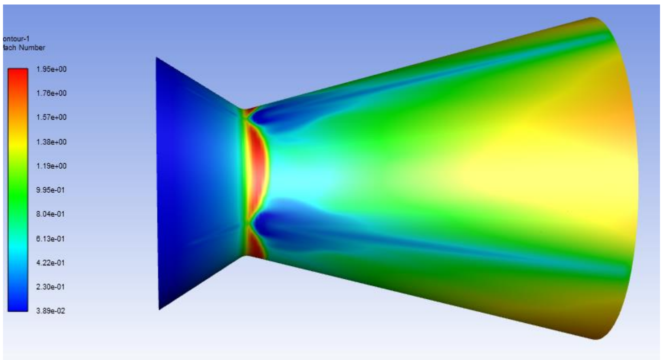
PRESSURE CONTOUR:



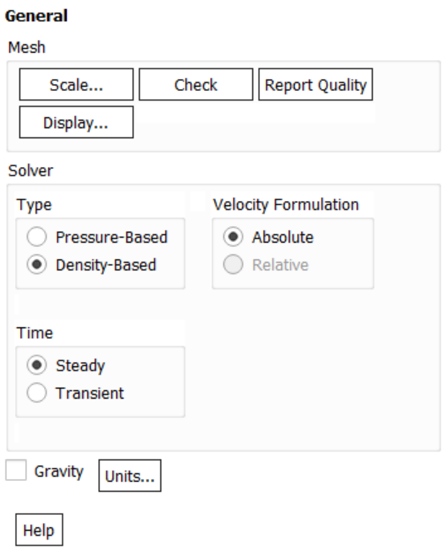
TEMPERATURE CONTOUR:

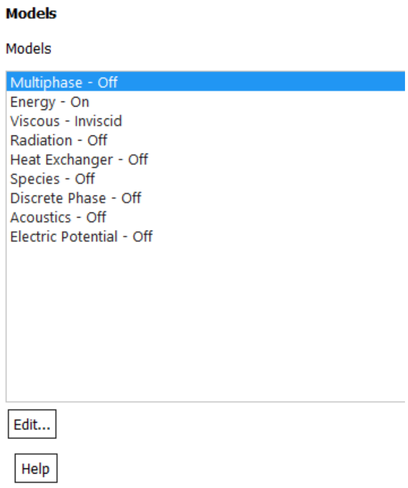


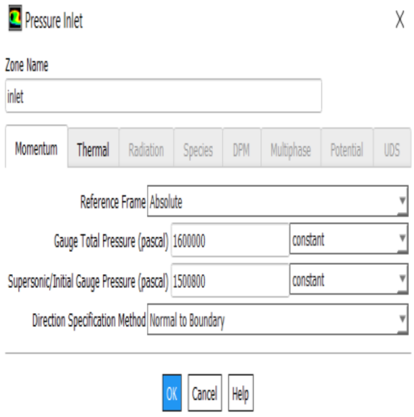
MACH NUMBER CONTOUR:

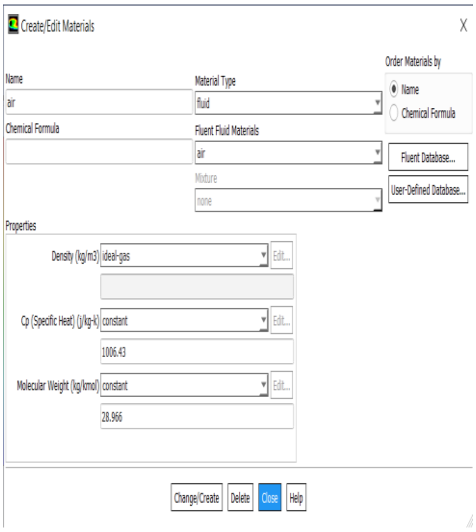


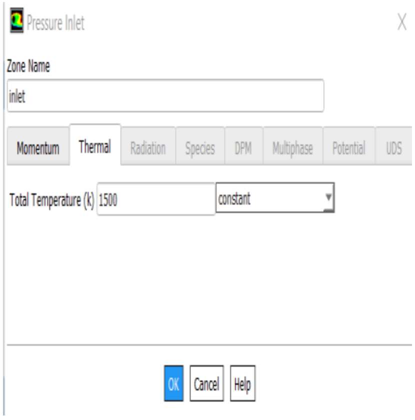
DETAILS:

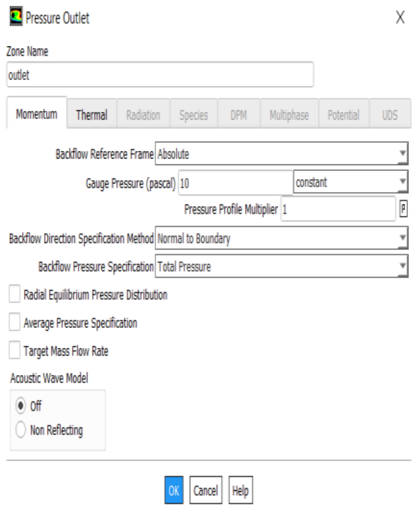

General
Mesh
Scale...
Check
Report Quality
Display...
Solver
Type
Pressure-Based
Density-Based
Velocity Formulation
Absolute
Relative
Time
Steady
Transient
Gravity
Units...
Help

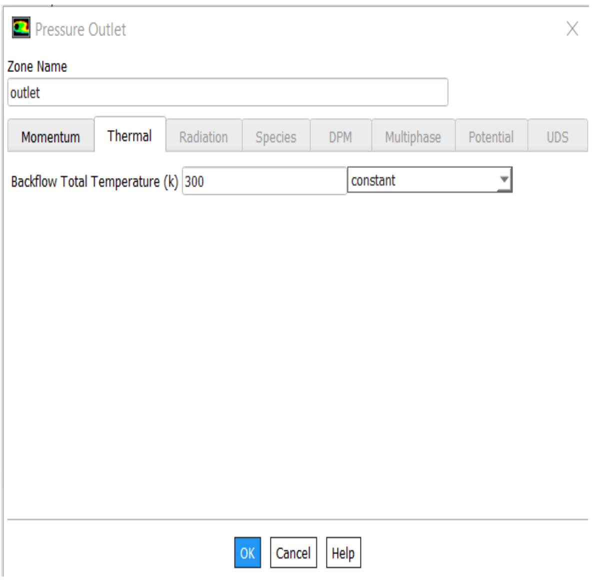

Models
Models
Multiphase - Off
Energy - On
Viscous - Inviscid
Radiation - Off
Heat Exchanger - Off
Species - Off
Discrete Phase - Off
Acoustics - Off
Electric Potential - Off
Edit...
Help

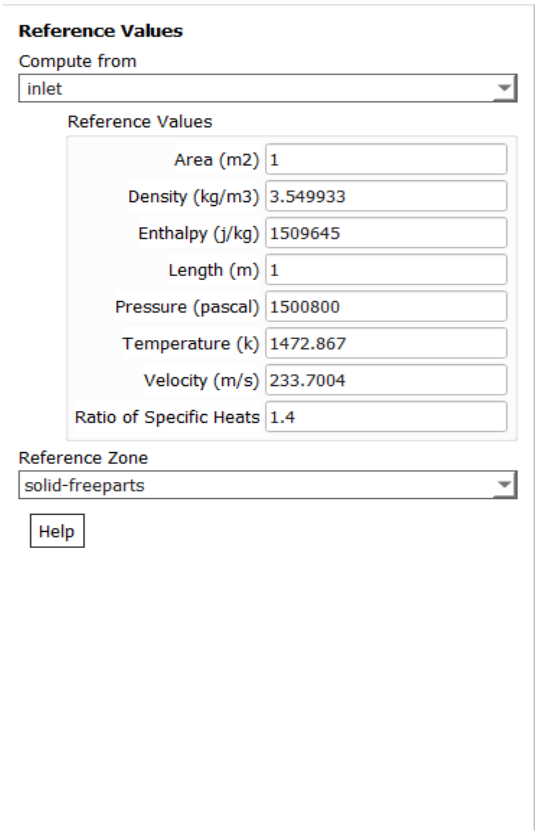

Pressure Inlet
Zone Name
inlet
Momentum
Thermal
Radiation
Species
DPM
Multiphase
Potential
UDS
Reference Frame
Absolute
Gauge Total Pressure (pascal)
1600000
constant
Supersonic/Initial Gauge Pressure (pascal)
1500800
constant
Direction Specification Method
Normal to Boundary
OK
Cancel
Help

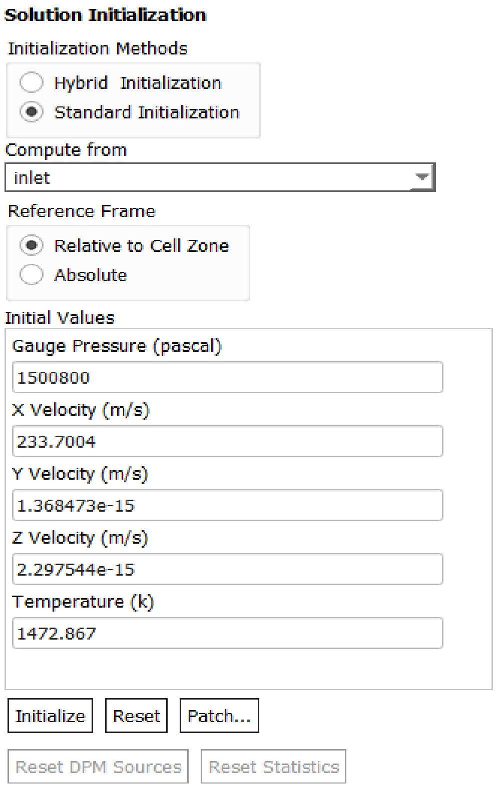

Create/Edit Materials
Name
air
Material Type
fluid
Order Materials by
Name
Chemical Formula
Chemical Formula
Fluent Fluid Materials
air
Fluent Database...
Mixture
none
User-Defined Database...
Properties
Density (kg/m3)
ideal-gas
Edit...
Cp (Specific Heat) (j/kg-k)
constant
Edit...
1006.43
Molecular Weight (kg/kmol)
constant
Edit...
28.966
Change/Create
Delete
Close
Help

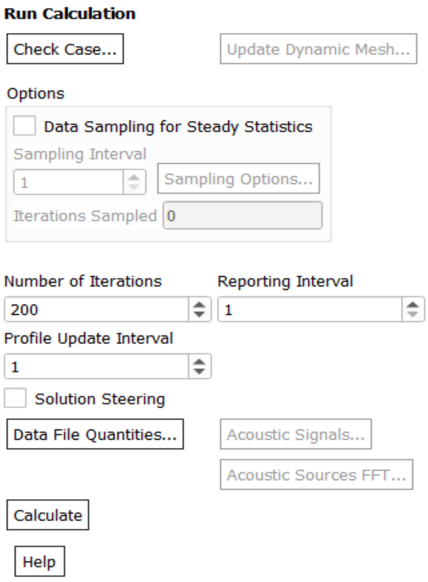

Pressure Inlet
Zone Name
inlet
Momentum
Thermal
Radiation
Species
DPM
Multiphase
Potential
UDS
Total Temperature (k)
1500
constant
OK
Cancel
Help


Pressure Outlet
Zone Name
outlet
Momentum
Thermal
Radiation
Species
DPM
Multiphase
Potential
UDS
Backflow Reference Frame
Absolute
Gauge Pressure (pascal)
10
constant
Pressure Profile Multiplier
1
Backflow Direction Specification Method
Normal to Boundary
Backflow Pressure Specification
Total Pressure
Radial Equilibrium Pressure Distribution
Average Pressure Specification
Target Mass Flow Rate
Acoustic Wave Model
Off
Non Reflecting
OK
Cancel
Help


Pressure Outlet
Zone Name
outlet
Momentum
Thermal
Radiation
Species
DPM
Multiphase
Potential
UDS
Backflow Total Temperature (k) 300
constant
OK
Cancel
Help


Reference Values
Compute from
inlet
Reference Values
Area (m2) 1
Density (kg/m3) 3.549933
Enthalpy (j/kg) 1509645
Length (m) 1
Pressure (pascal) 1500800
Temperature (k) 1472.867
Velocity (m/s) 233.7004
Ratio of Specific Heats 1.4
Reference Zone
solid-freeparts
Help


Solution Initialization
Initialization Methods
Hybrid Initialization
Standard Initialization
Compute from
inlet
Reference Frame
Relative to Cell Zone
Absolute
Initial Values
Gauge Pressure (pascal)
1500800
X Velocity (m/s)
233.7004
Y Velocity (m/s)
1.368473e-15
Z Velocity (m/s)
2.297544e-15
Temperature (k)
1472.867
Initialize
Reset
Patch...
Reset DPM Sources
Reset Statistics


Run Calculation
Check Case...
Update Dynamic Mesh...
Options
Data Sampling for Steady Statistics
Sampling Interval
1
Sampling Options...
Iterations Sampled 0
Number of Iterations
200
Reporting Interval
1
Profile Update Interval
1
Solution Steering
Data File Quantities...
Acoustic Signals...
Acoustic Sources FFT...
Calculate
Help

ANALYTICAL METHOD (32°)

1. EXIT MACH:

M_e=V/a=562.3/331=1.69

M_e=1.69

2. EXIT TEMPERATURE:

$(T_e/T_t)=[1+((\gamma-1)/2)M_e^2]^{-1}$

$T_e=1250*[1+((1.4-1)/2)*(1.69)^2]^{-1}$

T_e=795.5K

3. EXIT PRESSURE:

$(P_e/P_t)=[1+((\gamma-1)/2)M_e^2]^{-(\gamma/\gamma-1)}$

$P_e=867885*[1+((1.4-1)/2)*(1.69)^2]^{-(1.4/1.4-1)}$

P_e=178497.72Pa

4. THRUST:

$F=\dot{m}V_e+(P_e-P_o)A_e$

F=(9.15*964)+(178497.72-0)*0.015392

F=11569.29N

4.9 COMPARISON OF RESULTS FOR VARIOUS CASES

Table 4.1: Comparison of Results for Various Cases

CASE	CONVERGENT ANGLE	PARAMETERS	CFD RESULTS	THEORETICAL RESULTS	ERROR %
1	24º	EXIT MACH	1.6	1.68	4.76
		EXIT TEMPERATURE	777.78K	767K	1.38
		EXIT PRESSURE	156083Pa	164942.29Pa	5.37
		THRUST	12719N	11565.69N	9.06
2	26º	EXIT MACH	1.7	1.67	1.76
		EXIT TEMPERATURE	779K	770.32K	1.11
		EXIT PRESSURE	157922Pa	165986.29Pa	4.85
		THRUST	13610.7N	11867N	12.81
3	28º	EXIT MACH	1.6	1.7	5.88
		EXIT TEMPERATURE	779.5K	792.125K	1.59
		EXIT PRESSURE	156498Pa	171799.28Pa	8.9
		THRUST	10427.3N	9740.79N	6.58
4	30°	EXIT MACH	1.6	1.67	4.19
		EXIT TEMPERATURE	780.6K	833.82K	6.38
		EXIT PRESSURE	156660Pa	181864.2Pa	13.85
		THRUST	12656.5N	11584.3N	8.47
5	32º	EXIT MACH	1.58	1.69	6.5
		EXIT TEMPERATURE	775K	795.5K	2.57
		EXIT PRESSURE	156783Pa	178497.72Pa	12.16
		THRUST	12640N	11569.29N	8.47

CHAPTER – 5

CONCLUSION AND FUTURE WORK

5.1 CONCLUSION

We have discussed the fundamental concepts behind a converging- diverging nozzle for rocket in this Thesis. Through this research and analysis, we were able to determine the values of variation in nozzle parameters using both theoretical formulae and CFD. Thus, we draw the conclusion that the values obtained using both of these methods are consistent.

A rocket nozzle with a convergent angle of 26° is the most suitable and offers the optimum mach number and thrust. According to the numerical and flow characteristics of the Nozzle with various angles achieved in this project. This optimal design when implemented can result in increased nozzle performance and as a result, an improved propulsion system performance can be achieved. According to the findings of the study, the mach number and thrust at the exit of the nozzle are respectively 1.7 and 13610.7N when the convergent angle is 26°.

5.2 FUTURE SCOPE

- Structural analysis of the nozzle material can be carried out in future.
- Different combination of nozzles can be considered for the CFD analysis.
- Conducting an experimental investigation.
- Comparing and analyzing the outcomes of the numerical technique with the experiments.

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