CFD Analysis of Convergent Divergent Nozzle in at Sonic Velocities

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Abstract- *The Principle motivation behind a nozzle is to quicken the stream to higher leave speeds. The liquid quickening depends on the plan criteria and qualities. To accomplish great execution attributes with least vitality misfortunes a nozzle must fulfill all the outline prerequisites at all working conditions. This is conceivable just when the nozzle hypothesis is thought to be isentropic independent of the adjustments in weight, temperature and thickness which is for the most part caused because of development of a Shock Wave. The postulation concentrates on the plan, advancement and enhancement of a Supersonic Convergent-Divergent Nozzle where the expository outcomes are approved utilizing hypothesis computations. The recreation work is completed for CD Nozzles with various points of uniqueness keeping alternate sources of info settled. The goal of the proposed theory is to demonstrate the best Expansion proportion, Nozzle Pressure proportion (NPR) and Nozzle Area Ratio(NAR) where the push got by the supersonic nozzle is most extreme. The recreation is then rehashed for extension gas the consequences of which are later contrasted with standard air with indicate which has better execution qualities.*

The alternate angle of divergence will result in the higher expansion ratios therefore subjecting to higher efficiencies.

I. INTRODUCTION

The purpose of this applet is to simulate the operation of aconvergent and divergent nozzle, perhaps the most important and basic piece of engineering hardware associated with propulsion and the high speed flow of gases. This device was invented by Carl de Laval toward the end of the l9th century and is thus often referred to as the 'de Laval' nozzle. This applet is intended to help students of Compressible aerodynamics visualizes the flow through this type of nozzle at a range of conditions.

A simple example:

To get a basic feel for the behavior of the nozzle imagine performing the simple experiment. Here we use a converging diverging nozzle to connect two air cylinders. Cylinder A contains air at high pressure, and takes the place of the chamber.

The CD nozzle exhausts this air into cylinder B, which takes the place of the tank.

The reason for this behavior has to do with the way the flows behave at Mach 1, i.e. when the flow speed reaches the speed of sound. In a steady internal flow (like a nozzle) the Mach number can only reach 1 at a minimum in the cross-sectional area. When the nozzle isn't choked, the flow through it is entirely subsonic and, if you lower the back pressure a little, the flow goes faster and the flow rate increases. As you lower the back pressure further the flow speed at the throat eventually reaches the speed of sound (Mach 1). Any further lowering of the back pressure can't accelerate the flow through the nozzle anymore, because that would entail moving the point where M=1 away from the throat where the area is a minimum, and so the flow gets stuck. The flow pattern downstream of the nozzle (in the diverging section and jet) can still change if you lower the back pressure further, but the mass flow rate is now fixed because the flow in the throat (and for that matter in the entire converging section) is now fixed too.

It is hoped that through the production of this nozzles, the advances of space vehicle and rocket designs can continue forward as those who would have never had the time , space, and funding for a full-scale test facility can take a step closer in their research.

NOZZLE ELEMENTS

The nozzle we are considering is a convergent-divergent nozzle with rectangular cross-section. In our nozzle we are assuming inlet flow perpendicular to the exit flow. This makes nozzle analysis quite complicated due to **3-D** flow characteristics.

DESIGN PARAMETERS

Supersonic wind tunnel nozzle design merely depends upon cross-section from inlet of nozzle to exit of nozzle. By varying the cross-section area of the nozzle we can obtain different results. In this nozzle we are assuming throat area to be constant and varying inlet cross-section area for obtaining better results.

MODELLING OF NOZZLE

Nozzle is a arbitrary structure with varying cross-section areas. Modeling a nozzle is a typical task due to it contour, we have used solid works for modeling nozzle. We have varied convergent section of nozzle and model different nozzles.

ANALYSIS OF NOZZLE

There are different parameters on which nozzle performance depends upon. Here nozzle is analyzed to get a stabile supersonic flow at the exit. To obtain the supersonic flow we are varying area as well as input pressure and plotting the results which are keenly be observed for sati factorable results. For the analysis of the nozzle we are using Ansys module which is analysis software

II. LITERATURE

OPERATIONS OF CD NOZZLES:

- Figure (a) shows the flow through the nozzle when it is completely subsonic (i.e. nozzle isn't choked). The flow accelerates out of the chamber through the converging section, reaching its maximum (subsonic) speed at the throat. The flow then decelerates through Nth diverging section and exhausts into the ambient as a subsonic jet. Lowering the back pressure in this state increases the flow speed everywhere in the nozzle.
- Further lowering p_b results in figure (b). The flow pattern is exactly the same as in subsonic flow, except that the flow speed at the throat has just reached Mach 1. Flow through the nozzle is now choked since further reductions in the back pressure can't move the point of M=1 away from the throat. However, the flow pattern in the diverging section does change as the back pressure is lowered further.
- As p_b is lowered below that needed to just choke the flow a region of supersonic flow forms just downstream of the throat. Unlike a subsonic flow, the supersonic flow accelerates as the area gets bigger. This region of supersonic acceleration is terminated by a normal shock wave. The shock wave produces a near-instantaneous deceleration of the flow to subsonic speed. This subsonic flow then decelerates through the remainder of the diverging section and exhausts as a subsonic jet. In this regime if the back pressure is lowered or raised the length of supersonic flow in the diverging section before the shock wave increases or decreases, respectively.
- If p_b is lowered enough the supersonic region may be extended all the way down the nozzle until the shock is sitting at the nozzle exit, figure (d). Because of the very long region of acceleration (the entire nozzle length) the flow speed just before the shock will be very large. However, after the shock the flow in the jet will still be subsonic.
- Lowering the back pressure further causes the shock to bend out into the jet, figure (e), and a complex pattern of shocks and reflections is set up in the jet which will now involve a mixture of subsonic and supersonic flow, or (if the back pressure is low enough) just supersonic flow. Because the shock is no longer perpendicular to the flow near the nozzle walls, it deflects it inward as it leaves the exit producing an initially contracting jet. We refer to this as over-expanded flow because in this case the pressure at the nozzle exit is lower than that in the ambient (the back pressure)- i.e. the flow has been expanded by the nozzle too much.
- A further lowering of the back pressure changes and weakens the wave pattern in the jet. Eventually, the back pressure will be lowered enough so that it is now equal to the pressure at the nozzle exit. In this case, the waves in the jet disappear altogether, figure (f), and the jet will be uniformly supersonic. This situation, since it is often desirable, is referred to as the 'design condition‘, Pe=Pa.
- Finally, if the back pressure is lowered even further we will create a new imbalance between the exit and back pressures (exit pressure greater than back pressure), figure (g). In this situation, called under-expanded, expansion waves that produce gradual turning and acceleration in the jet form at the nozzle exit, initially turning the flow at the jet edges outward in a plume and setting up a different type of complex wave pattern.
- Summary Points to Remember:
- When the flow accelerates (sub or supersonically) the pressure drops
- The pressure rises instantaneously across a shock
- The pressure throughout the jet is always the same as the ambient (i.e. the back pressure) unless the jet is supersonic and there are shocks or expansion waves in the jet to produce pressure differences

OVER EXPANDED NOZZLE:

The rocket's nozzle is designed to be efficient at altitudes above sea level, and, at engine start, the flow is over-expanded, that is, the exhaust gas pressure, pe, is higher than the supersonic isentropic exit pressure but lower than the ambient pressure, pa. This causes an oblique shock to form at the exit plane of the nozzle. To reach ambient pressure, the gases undergo compression as they move away from the nozzle exit and pass through the oblique shock wave standing at the exit plane. The flow that has passed through the shock wave will be turned towards the center line .At the same time, the oblique shock wave, directed toward the center line of the nozzle, cannot penetrate the center plane since the center plane acts like a streamline. This causes the oblique shock wave to be reflected outward from the center plane.

. The gas flow goes through this reflected shock and is further compressed but the flow is now turned parallel to the centerline. This causes the pressure of the exhaust gases to increase above the ambient pressure. The reflected shock wave now hits the free jet boundary called a contact discontinuity (or the boundary where the outer edge of the gas flow meets the free stream air). Pressure is the same across this boundary and so is the direction of the flow. Since the flow is at a higher pressure than ambient pressure, the pressure must reduce. Thus, at the reflected shock wave-contact discontinuity intersection, expansion waves of the Prandtl-Meyer (P-M) type are set up to reduce the pressure to pa. These expansion waves are directed towards the centerline of the nozzle. The gas flow passing through the Prandtl-Meyer expansion waves turn away from the centerline .The Prandtl-Meyer expansion waves in turn reflect from the center plane towards the contact discontinuity .The gas flow passing through the reflected Prandtl-Meyer waves is now turned back parallel to the centerline but undergoes a further reduction of pressure.

PRANDTL-MEYER:

The reflected Prandtl-Meyer waves now meet the contact discontinuity and reflect from the contact discontinuity towards the centerline as Prandtl-Meyer compression waves. This allows the gas flow to pass through the Prandtl-Meyer compression waves and increase its pressure to ambient pressure, but passage through the compression waves turns the flow back towards the centerline. The Prandtl-Meyer compression waves now reflect from the center plane as compression waves further increasing the pressure above ambient, but turning the flow parallel to the nozzle centerline. The flow process is now back to when the flow had just passed through the reflected shock wave i.e., the flow pressure is above ambient and the flow is parallel to the centerline .This process of expansion-compression wave formation begins anew and continues until the pressure of the gases are the same as the ambient pressure and the flow is parallel to the centerline of the nozzle.

These expansion and compression waves that interact with each other, leads to the diamond patterns seen. Ideally, this process would continue without end; but a turbulent shear layer created by the large velocity differences across the contact discontinuity will dissipate the wave patterns (see the diamond pattern for the SR-71 Blackbird at the beginning of this section). At very high altitudes where the ambient pressure is less than the exhaust pressure of the gases, the flow is under expanded - the exhaust gases are exiting the nozzle at pressures below the supersonic isentropic exit pressure which is also the ambient pressure. Thus, the flow is at the same condition (pexhaust > pa) as the flow was after it passed through the reflected oblique shock wave when the rocket was at sea level. To reach ambient pressure, the exhaust gases expand via Prandtl-Meyer expansion waves .This expansion occurs by the gases turning away from the centerline of the rocket engine .Therefore, the exhaust plume is seen to billow out from the rocket nozzle.

EXPANSION AREA RATIO:

Most important parameter in nozzle design is expansion area ratio, e Fixing other variables (primarily chamber pressure) → only one ratio that optimizes performance for a given altitude (or ambient pressure)

However, rocket does not travel at only one altitude Should know trajectory to select expansion ratio that maximizes performance over a range of ambient pressures See Lecture Notes on Isentropic Nozzle Calculations for more DetailsOther factors must also be considered

Nozzle weight, length, manufacturability, cooling (heat transfer), and aerodynamic characteristics.

III. RESULTS

Case 1 With Normal Angle 15 degree

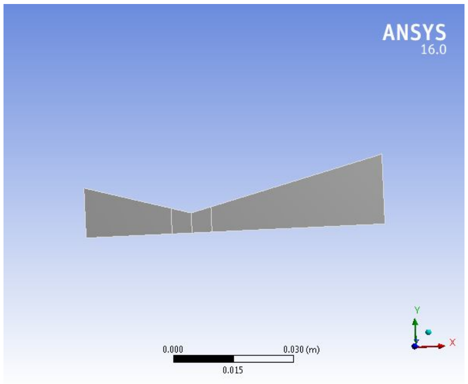


Fig 1: Axi-symmetrical model of c-d nozzle

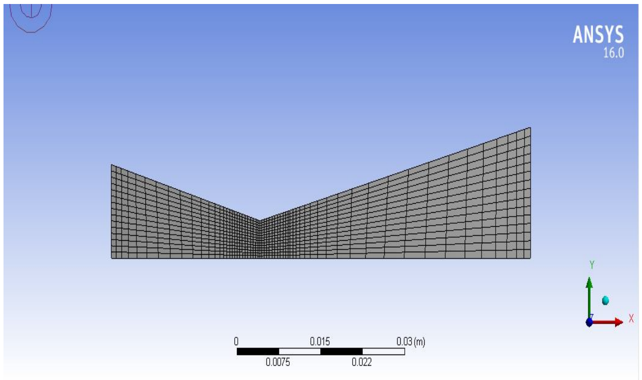


Fig 2: Meshed object

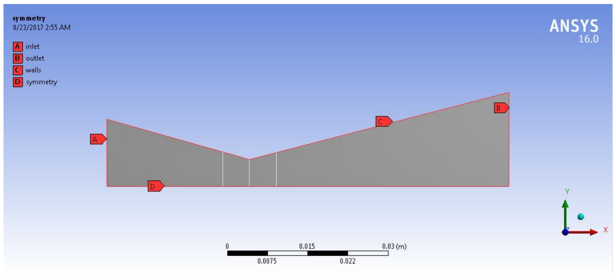


Fig 3: Symmetry

Boundary Conditions

Contours and plots

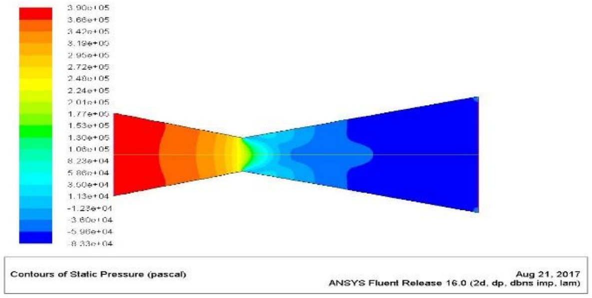


Fig 4 Pressure distribution

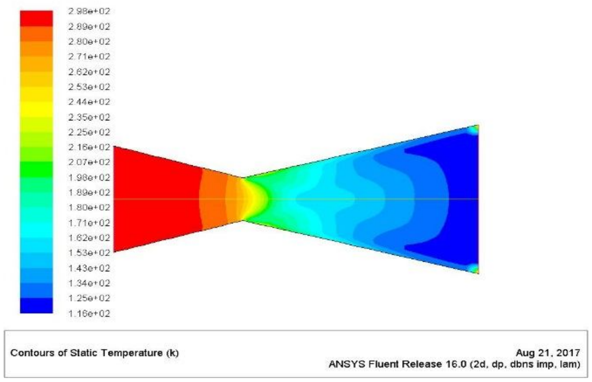


Fig 5:Contours of static temperature (k)

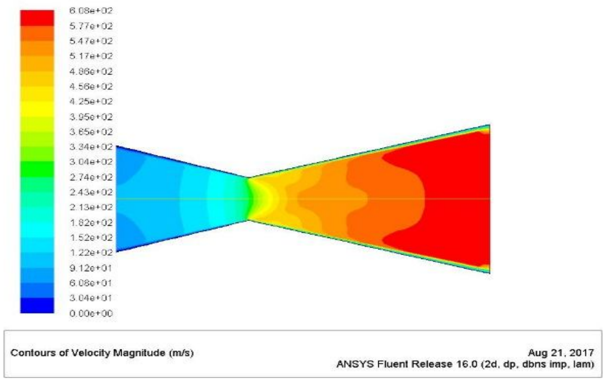


Fig 6: Contours of velocity Magnitude

Plots

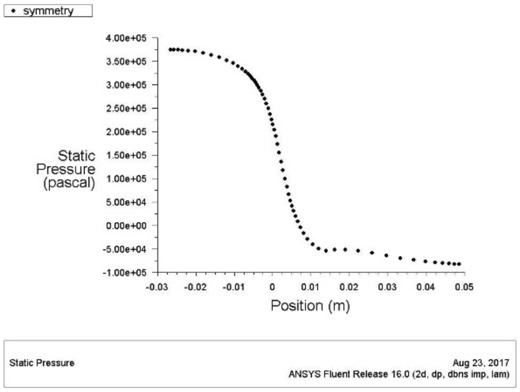


Fig 7: 15 degree attack angle Static Pressure plot

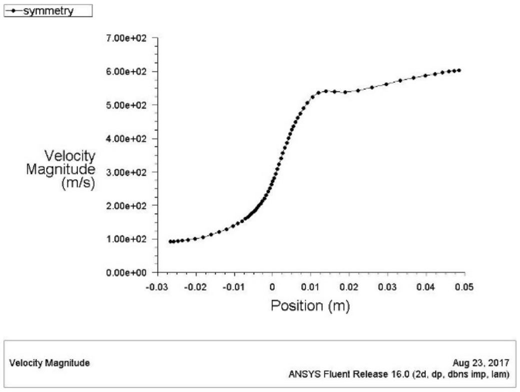


Fig 8: 15 degree attack angle Velocity plot

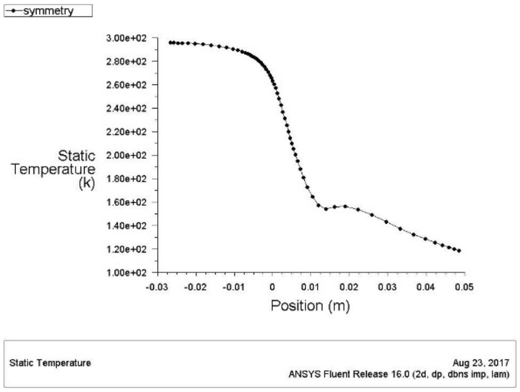


Fig.9: 15 degree attack angle temperature plot

Case 2 With Staggered angle (20 degrees)

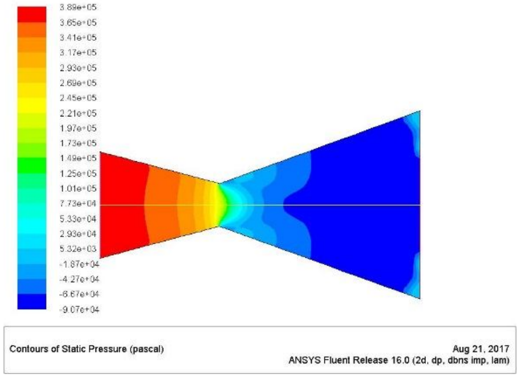


Fig10: Pressure Contour 20 degree

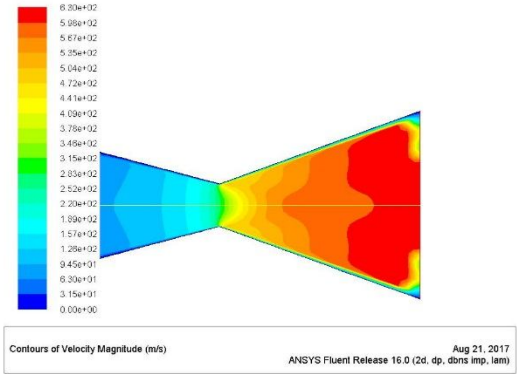


Fig 11: Velocity contour 20 degree

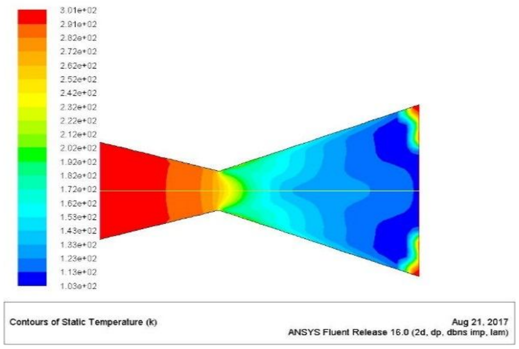


Fig 12: Temperature contour 20 degree

X-y Plots 20 degree attack angle

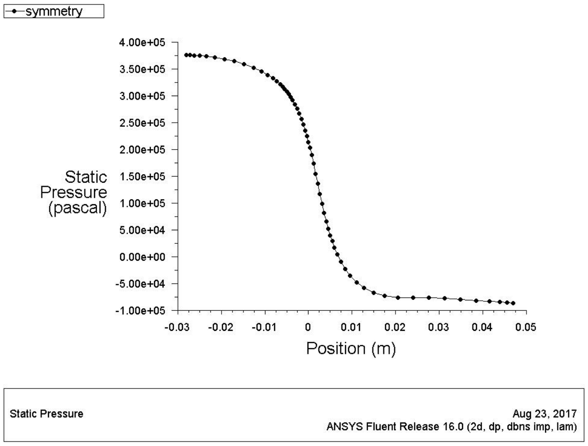


Fig 13: X-y plot 20 degree attack angle

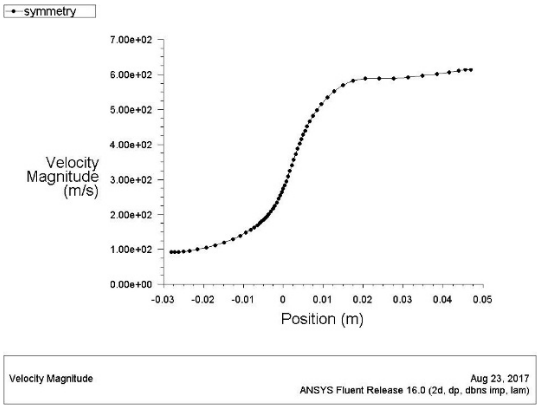


Fig 14: X-y plot 20 degree Attack angle Velocity.

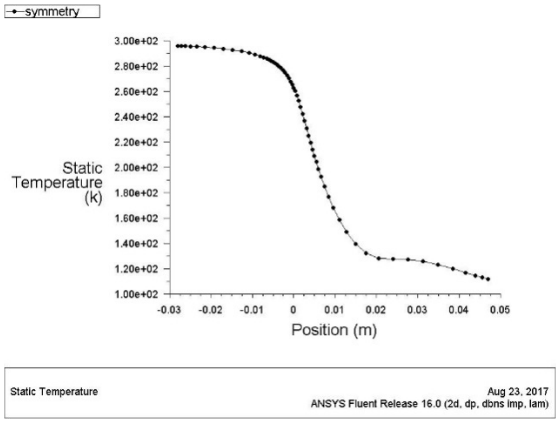


Fig 15: X-y Plot 20 degree attack angle Temperature

Case-3 With Semi Staggered attack (23degrees)

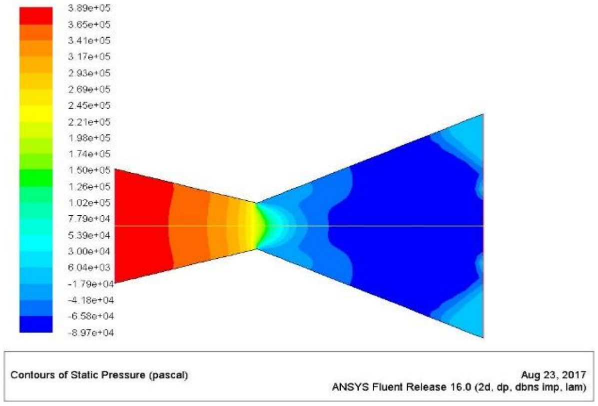


Fig 16: Pressure Contour with 23 degree attack angle

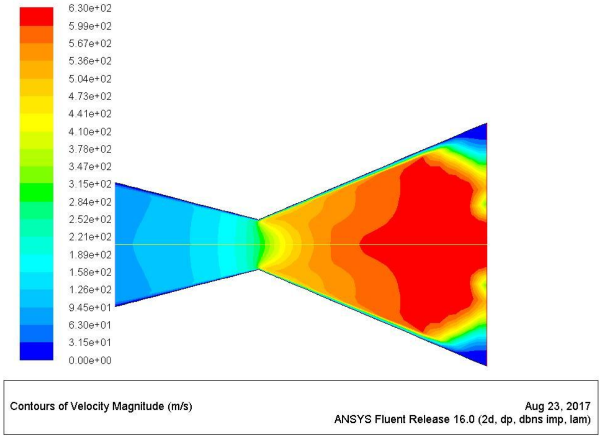


Fig 17: Velocity With 23 degree attack angle.

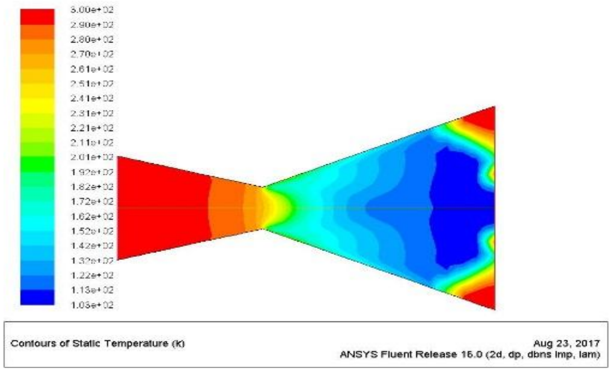


Fig 18: Temperature Distribution with 23 degree attack angle

X-Y plots with 23 degree Divergent angle

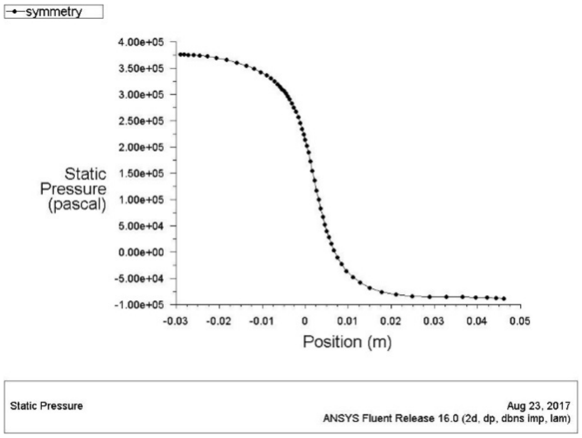


Fig 19: Pressure plot with 23 degree

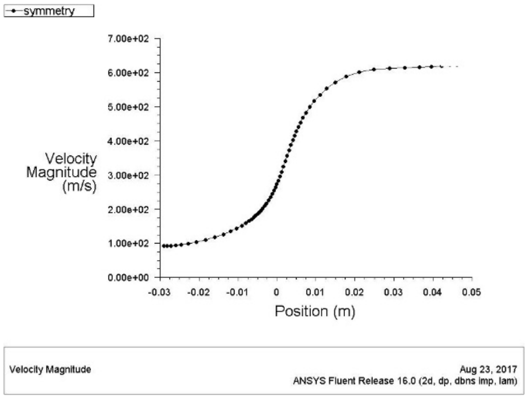


Fig 20: Velocity with 23 degree angle

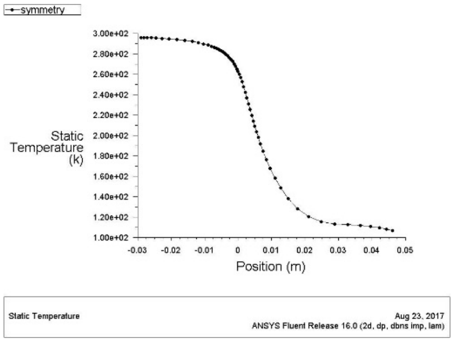
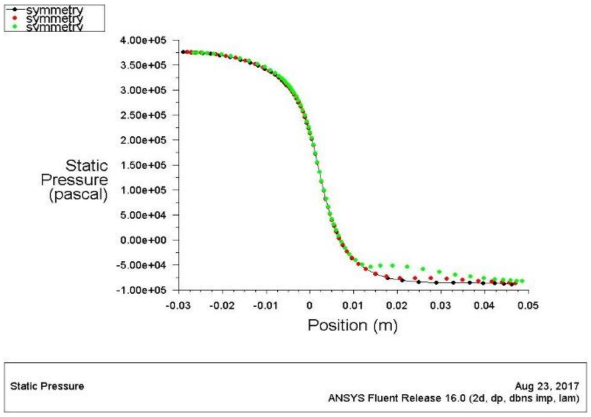


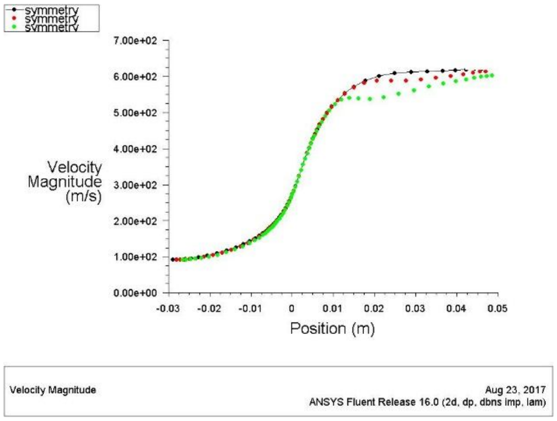
Fig 21: Temperature plot with 23 degree attack angle

IV. CONCLUSION

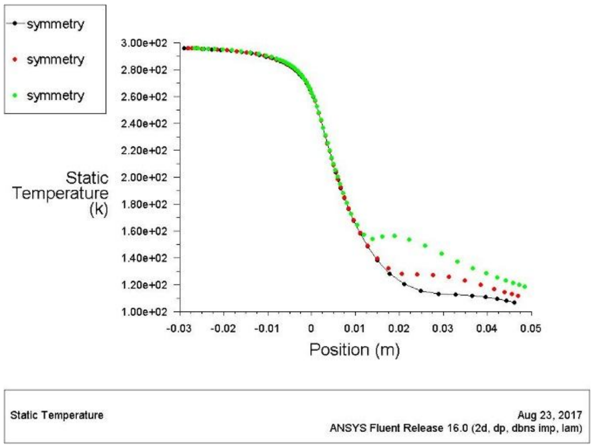
The effect of Diverging nozzle in all three cases compared with the nominal velocity will be compared in below graphs from the obtained results done in cfd we can say that uniform distribution in the flow will be occurring in normal angle that is case 1 with 15 degree and whereas end to end distributions are not possible in 20 degrees and 23 degrees where as velocity is concerned increase in attack angle results in the increase in velocity the same is observed in the below graphs.



Pressure Distribution in all 3 cases Black curve represents Case 3 Red Represents Case 2 and Green represents case 1



Velocity Distribution in all 3 cases Black curve represents Case 3 Red Represents Case 2 and Green represents case 1



Temperature Distribution in all 3 cases Black curve represents Case 3 Red Represents Case 2 and Green represents case 1

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Maddula Venkata Swamy was born in Gurajada, Pamidimukkala Mandal, and Krishna District, India in 1986. He received the B.Tech Degree in Mechanical Engineering from the JNTU, Kakinada, India in 2009. Later He joined the Department of Mechanical engineering, VKR&VNB Polytechnic, Gudivada as Lecturer in 2010. He received M.Tech Degree in Mechanical Engineering from the JNTU, Kakinada, India in 2014. Later He joined the Department of Mechanical engineering, VKR&VNB Polytechnic, Gudivada as Lecturer in 2014.There after, He joined the Department of Mechanical Engineering, DJR college of Engineering and Technology, Gudavalli, as a Assistant professor in 2016.