CFD ANALYSIS OF DE-LAVAL NOZZLE

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ABSTRACT

A nozzle is a device that is used to accelerate the velocity of fluid. A De-Laval Nozzle has a converging duct, throat, and a diverging duct at certain angle. This paper helps in explaining the various concepts related to De-Laval nozzle. In this paper the working of nozzle with the help of pressure variation has been discussed. The contours and graphs of pressure variation, velocity variation has been plotted against nozzle length for better understanding of the concept. The position of normal shockwave at different pressure-ratio in the diverging duct has been determined. The variation of flow parameters like Pressure, Velocity, and Temperature is visualized using Computational Fluid Dynamics.

Key words: *De-Laval Nozzle, Pressure-Ratio, Normal Shockwave, Ideal gas, Computational Fluid Dynamics, Ansys-Fluent.*

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1. INTRODUCTION

Nozzle is a device which is designed to control properties of fluid like pressure, density, temperature and velocity. The major application of nozzle is to increase the velocity of flow by converting pressure and heat into kinetic energy. Mostly in rockets or air breathing engines, it is used to produce thrust to gain lift. Fluid of subsonic velocities can be accelerated to supersonic velocities using a rocket engine nozzle. To design a nozzle the major requirement is the magnitude of thrust produced by the nozzle. The altitude at which it operates and the properties of working fluid which govern the flow are its molecular weight, specific heat at constant pressure or volume and specific heat ratio.

2. DE-LAVAL NOZZLE

De-Laval nozzle is mainly used to achieve supersonic velocities. De-Laval nozzle or Converging-Diverging Nozzle is the most widely used type of nozzle. It is in the shape of a tube pinched at the middle, making a perfectly balanced asymmetric hourglass shape. It is widely used in supersonic jet engines and steam turbines. They also have certain application in jet stream within astrophysics.

Converging nozzle has a cross section reducing up to the throat at which the fluid gains maximum velocity. However in a converging nozzle the fluid can be accelerated up to sonic speed [Ma=1]. Thus to increase the velocity of fluid up to supersonic speed [Ma>1] a diverging part is attached to the nozzle. This type of nozzle is known as Converging Diverging Nozzle or De-Laval Nozzle.

2.1. Operation

The speed of a gas (subsonic flow) will increase if the pipe carrying it narrows, because the mass flow rate is constant. The gas flowing is assumed to be isentropic. In a subsonic flow the gas is compressible and sound will propagate. At the throat, where cross section area is at its minimum, the gas velocity locally becomes sonic [Ma=1], a condition called chocked flow. As the nozzle cross sectional area increases the gas begins to expand, and the gas flow increase to supersonic velocities, where a sound wave will not propagate backwards through the gas as viewed in the frame of reference of the nozzle [Ma>1] It is not sufficient to force a fluid through nozzle to gain the supersonic velocity. Sometimes, the fluid may decelerate in the diverging section instead of accelerating if the back pressure is not in the range. Thus the state of nozzle flow is determined by the Overall Pressure Ratio.

Consider the following conditions,
1. When $P_0=P_b$
When $P_0=P_b$, There is no pressure difference and thus no flow through nozzle.

2. When $P_0>P_b>P_c$

The flow remains subsonic through the nozzle. The fluid velocity increases in converging section and reaches to maximum at the throat, but the velocity is still subsonic at the throat. Thus in the diverging part, fluid loses its energy and diverging part acts as diffuser. The pressure reduces up to throat and again increases in the diverging section.

3. When $P_b=P_c$

The throat pressure becomes P_* and fluid gains the sonic velocity at the throat. P_* is the minimum pressure at the throat and the velocity obtained is maximum velocity achieved by converging nozzle. Further reduction does not influence flow through the converging section, but influences flow through diverging section.

4. When $P_C>P_b>P_e$

The fluid that achieves the sonic velocity continues to accelerate to supersonic velocities in the
diverging section. As pressure decreases, acceleration comes to sudden stop. Normal shocks are developed at the section between throat and exit plane and thus there is sudden drop in the velocity and flow gets decelerated. Flow through shock is highly irreversible and cannot be approximated as isentropic flow.
When $P_b=P_e$ shockwave forms at exit plane. Thus the supersonic flow through the nozzle becomes
subsonic before leaving the nozzle as it crosses the normal shock.

5. When $P_e>P_b>0$

The flow in diverging section is supersonic and fluid expands to P_F at the nozzle exit with no normal shock. Thus analysis of flow can be done as isentropic flow. When $P_b=P_F$ however, the pressure inside the nozzle increases from P_F to P_b irreversibly in the wake of nozzle creating oblique shocks. The behavior of fluid expansion process is governed by exhaust pressure as well as pressure of external environment into which it exhausts. For minimum conversion of thermal energy into thrust, the exit pressure will be equal to the ambient pressure.

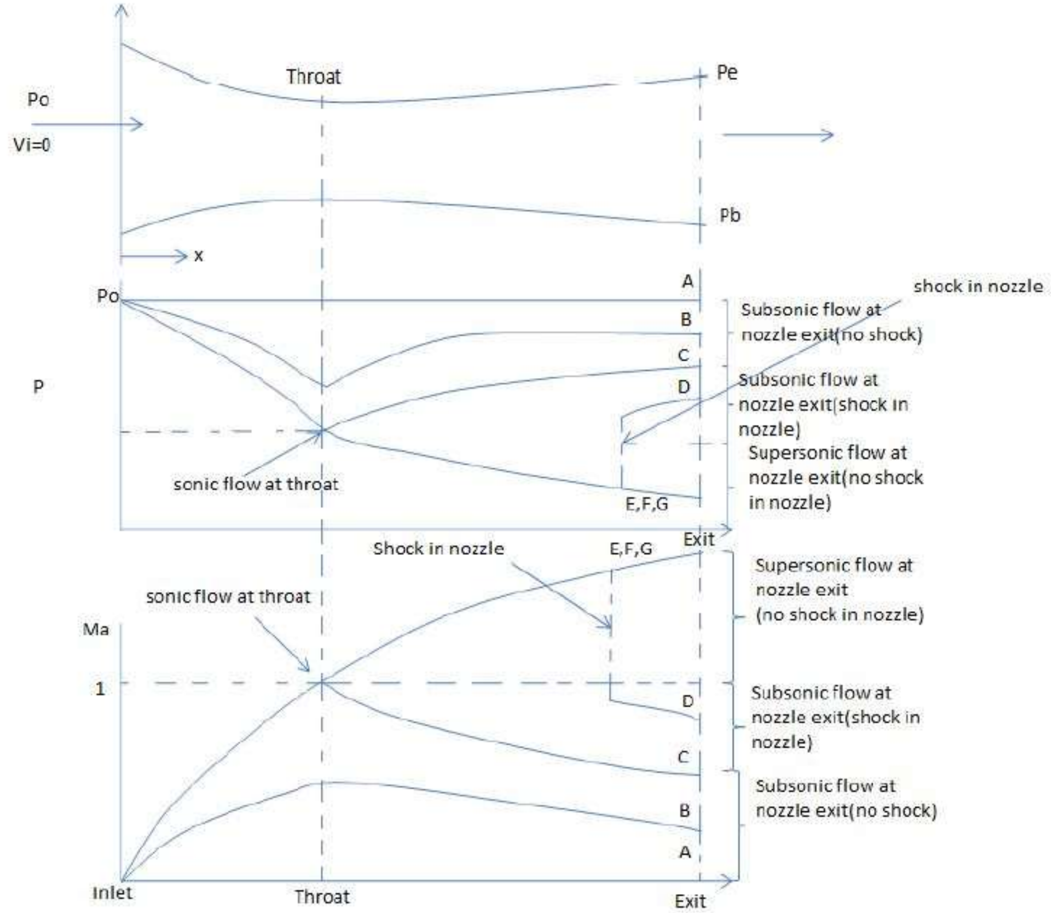


Fig -1: Pressure Conditions

2.2 Shockwave

For some back pressure values, abrupt changes in fluid properties occur in a very thin section of a De Laval nozzle under supersonic flow conditions, creating a shockwave.

Normal shocks

Shockwaves that occur in a plane normal to the direction of flow are normal shocks. The flow is supersonic before the shock and subsonic afterwards. Therefore the flow must change from supersonic to subsonic if a shockwave is to occur. The larger the Mach number before the shock, the stronger the shock will be. In the limiting case of Ma=1, the shock wave simply becomes a sound wave.

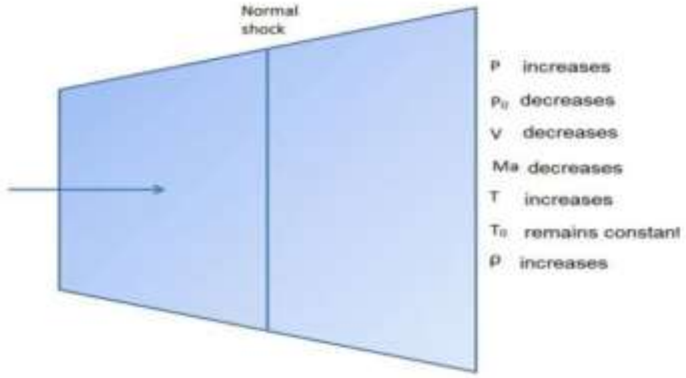


Fig -2 : Variation of parameters in shockwave

According to conservation of energy principle, the stagnation enthalpy remains constant across the shock; h01=h02. The stagnation temperature is also constant T01=T02. The stagnation pressure decreases across the shock, because of irreversibility, while the ordinary temperature rises drastically because of the conversion of kinetic energy into enthalpy due to a large drop in fluid velocity.

3. SIMULATION OF DE LAVAL NOZZLE

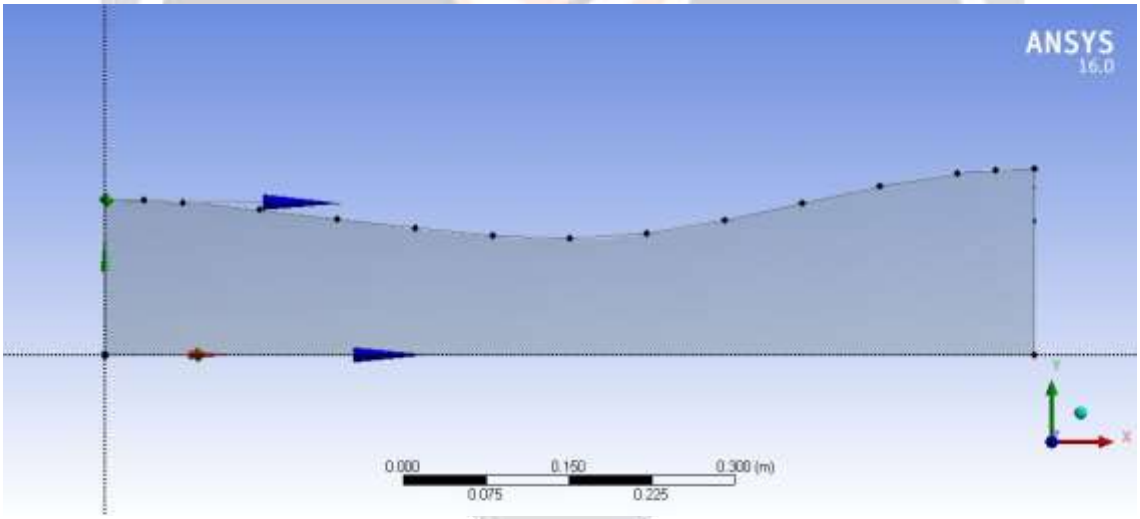


Fig -3: CAD Model of De-Laval Nozzle

Computer simulation of nozzle was done using computational fluid dynamics (CFD). CFD is method to solve complex problems involving fluid flow.

The above conditions were taken as mentioned in the previous section and the computer simulation that is the analysis was done using Ansys-Fluent. When we performed this analysis, we found out the variation of parameters as we did in the case of theoretical treatment.

The CFD Analysis was done in the following steps:

- Modelling
- Meshing
- Pre processing
- Solver/Processing
- Post processing

3.1. Modeling

The modeling of the De Laval nozzle was done in Ansys design modeler. The points were plotted first using construction point command and then they were joined using 3D curves. Lines from points option was also used to join the points. A 2D surface was finally created using surface from edges command. The nozzle dimensions are as follows

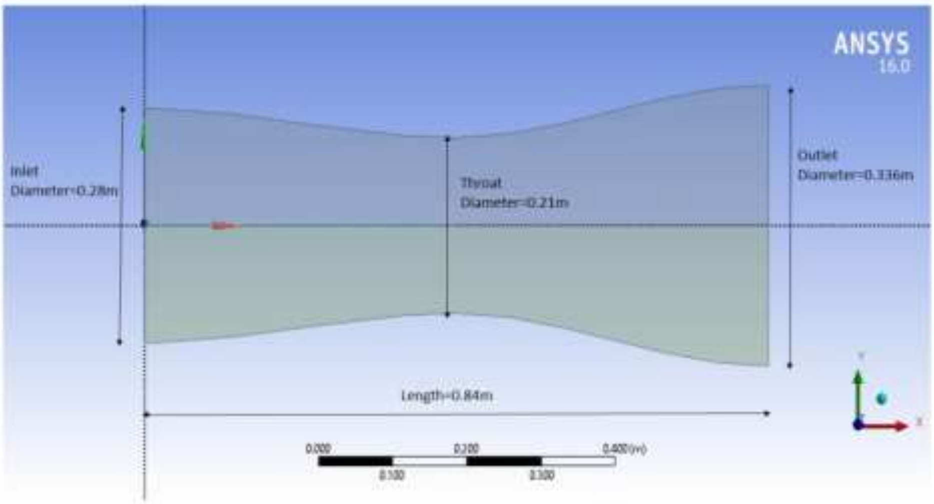


Fig -4 : De-laval Nozzle dimensions

Parameter	**Dimension**
Total Length of Nozzle (mm)	840
Inlet Diameter (mm)	280
Outlet Diameter (mm)	336
Throat Diameter (mm)	210
Convergence angle (deg)	30.55
Divergence angle (deg)	54.532

3.2. Meshing

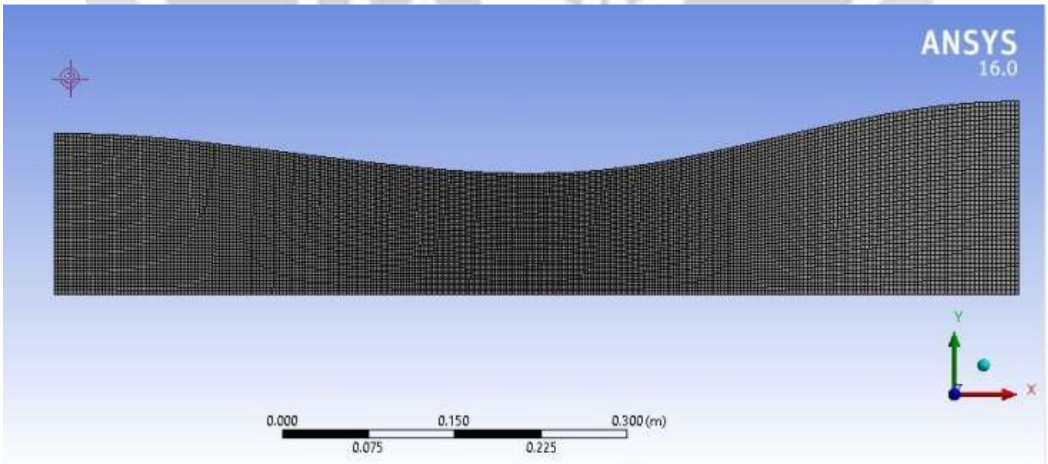


Fig -5: Meshed model of nozzle

The model created by the above dimensions was meshed in mesh mode of Ansys component systems. Meshing is nothing but converting an infinite number of particles model of finite number of particles. The details of mesh were Physics preference: CFD. The relevance of meshing was set to 100. The proximity and curvature option was selected, since nozzle is a curved object. The smoothing was high and num cells across gap were set to 50. The meshing was fine. Therefore number modes were calculated as 12760 and number of elements was 12427. Mapped face meshing was used for the two faces. The relevance center was set to fine and the elements used were of quadrilateral shape.

3.3. Pre Processing

The next step of the CFD after meshing is pre processing. In pre processing appropriate boundary conditions are applied to the meshed model. The pre processing was done in Ansys Fluent.

Table -1: Pre-processing Details

General	Solver Type: Density Based 2D Space: Planar Time: Steady
Materials	Density: Ideal Gas C_p : 1.006.43 J/kg K k : 1.4 Viscosity: $1.81*10^{-5}$ Pas Thermal Conductivity: 0.02619 W/mK Mean molecular mass : 28.966 g/mole

Now we will discuss various cases of pressure ratio variation i.e. by decreasing the outlet pressure .
Pressure Ratio = Outlet Pressure/ Inlet Pressure

Table -2: Pressure-Ratio

	Pressure Ratio
Case I	**0.96**
Case II	**0.92**
Case III	**0.88**
Case IV	**0.80**
Case V	**0.72**
Case VI	**0.64**
Case VII	**0.56**

Case I : Pressure Ratio = 0.96

Table -3: Pre-processing Details

Boundary Conditions	Inlet Pressure = 238828.2 Pa Inlet Temperature = 300 *K* Outlet Pressure = 229275.07 Pa Outlet Temperature = 176.32 *K*

Table -4: Solver Details

Solution Control	Courant number = 5
Solution Initialization	Compute from = inlet
Run Calculation	Number of iterations = 2500

The solution was converged after 2313 iterations.

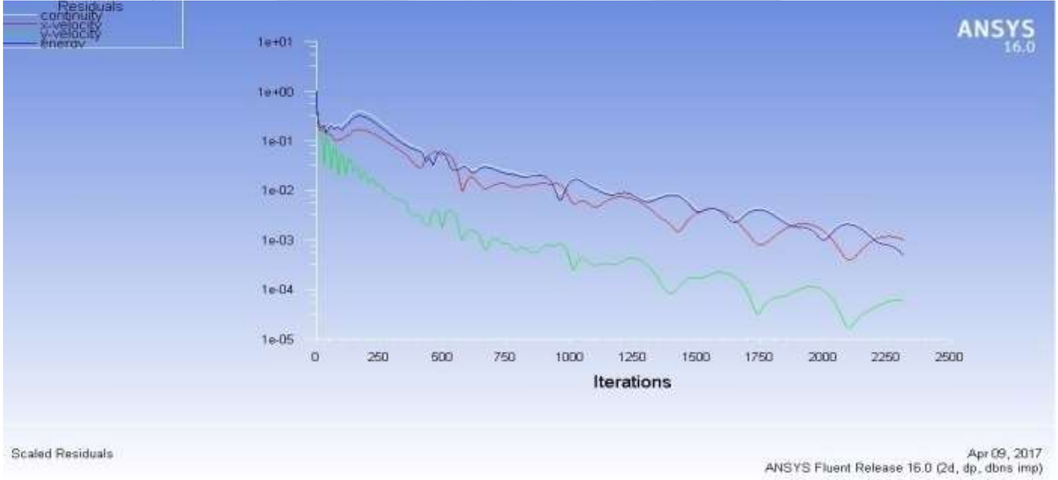


Fig -6: Scaled Residuals

Post Processing/Result

Velocity Variation

Velocity first increases to throat and then decreases . It is minimum at the inlet section and maximum at the throat and then decreases in the outlet section. Minimum velocity is 82.82 m/s. and maximum velocity is 155.17 m/s.

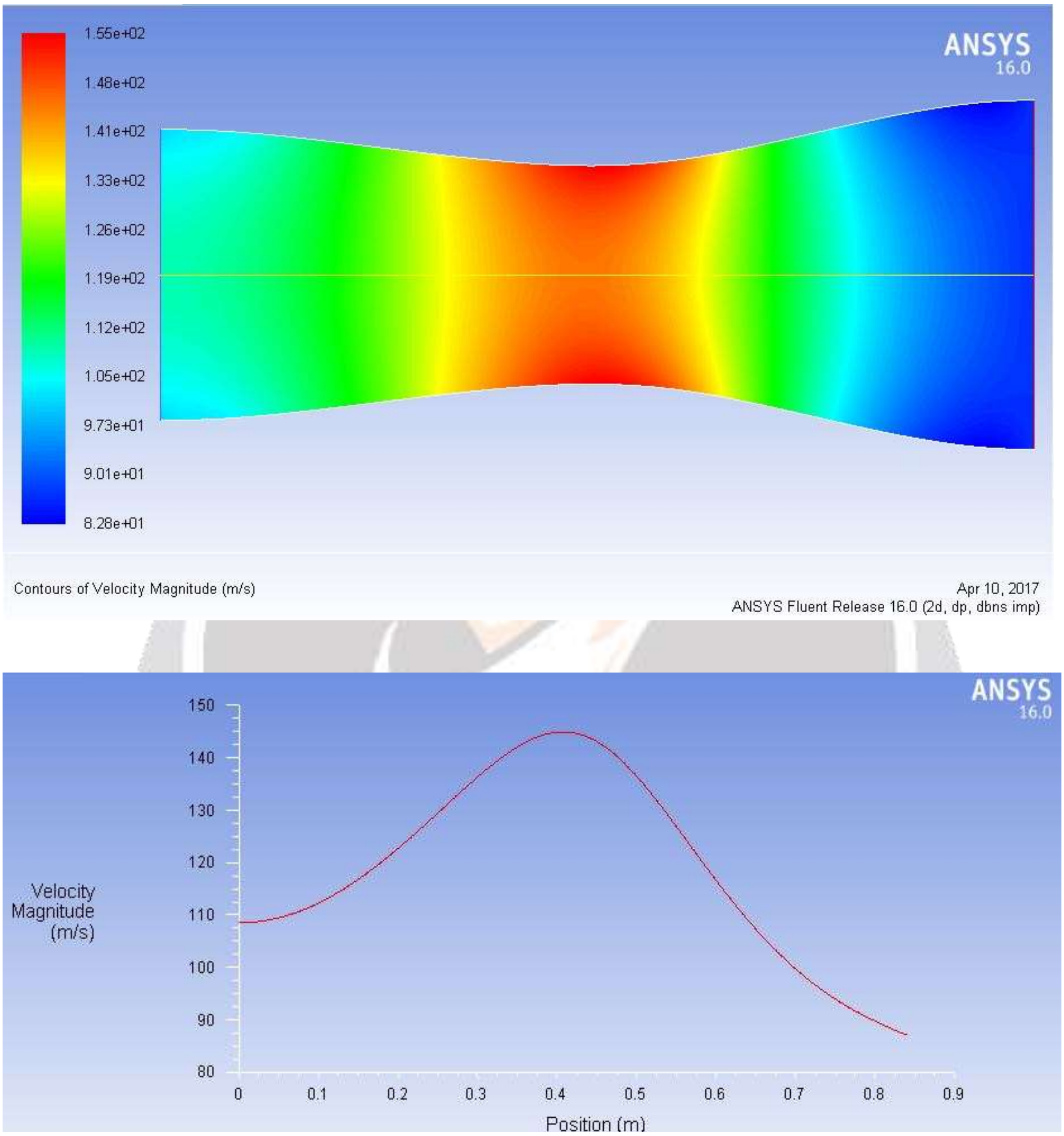


Fig -7: Velocity Contour and Graph (m/s)

Pressure Variation

Pressure is maximum at the outlet section and minimum at the throat. Maximum value of pressure is 230217.7 Pa and minimum value is 208049.2 Pa.

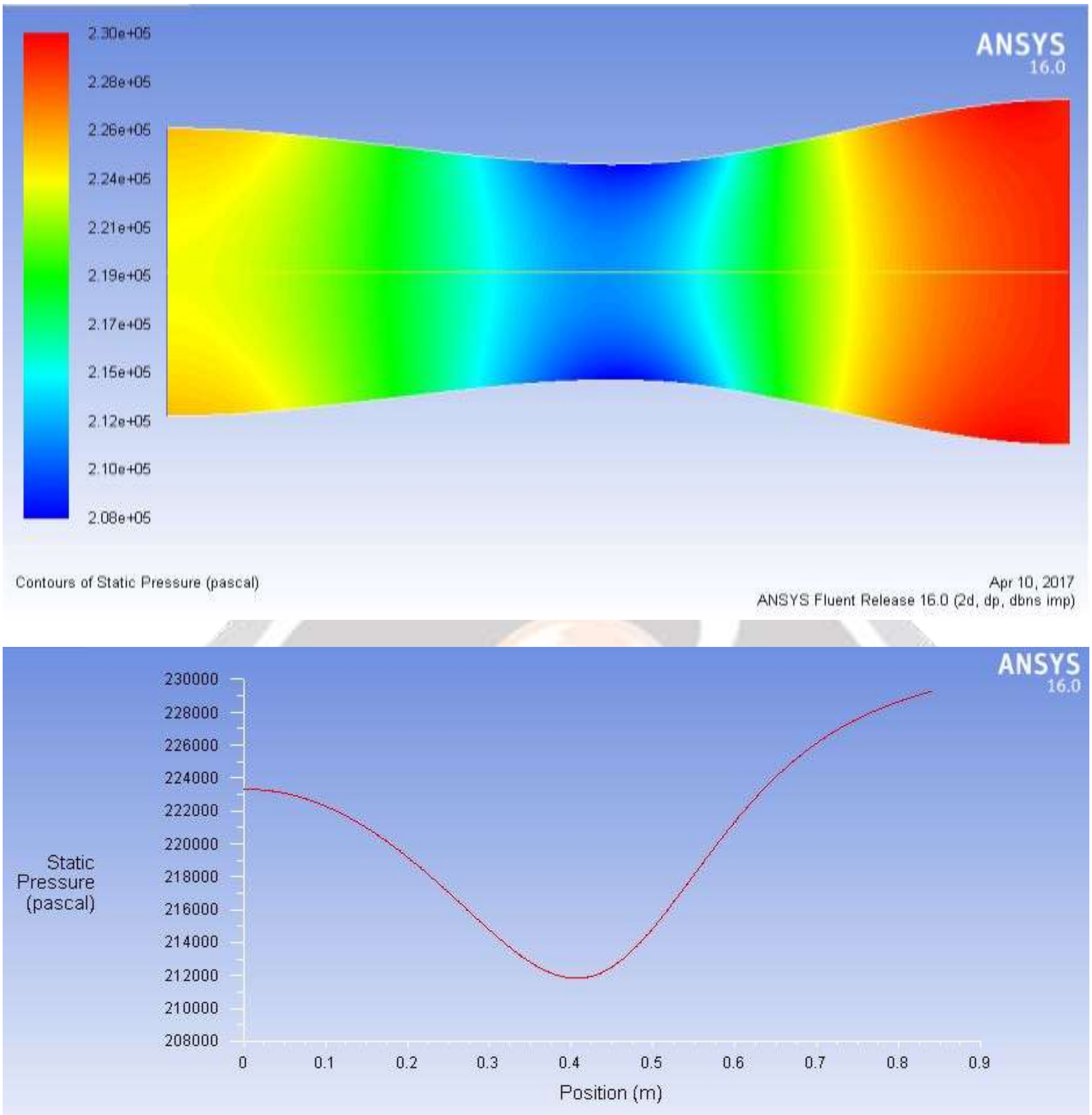


Fig -8: Pressure contour and Graph (Pa)

Case II : Pressure Ratio = 0.92

Table -5: Pre-processing Details

Boundary Conditions	Inlet Pressure = 238828.2 Pa Inlet Temperature = 300 *K* Outlet Pressure = 219721.94 Pa Outlet Temperature = 176.32 *K*

Table -6: Solver Details

Solution Control	Courant number = 5
Solution Initialization	Compute from = inlet
Run Calculation	Number of iterations = 3000

The solution was converged after 2925 iterations.

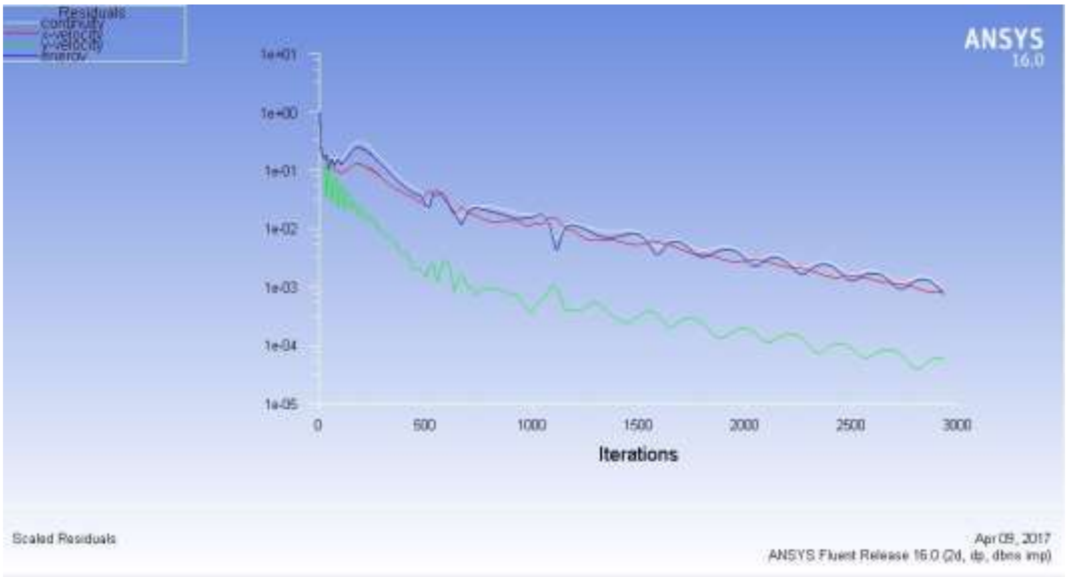
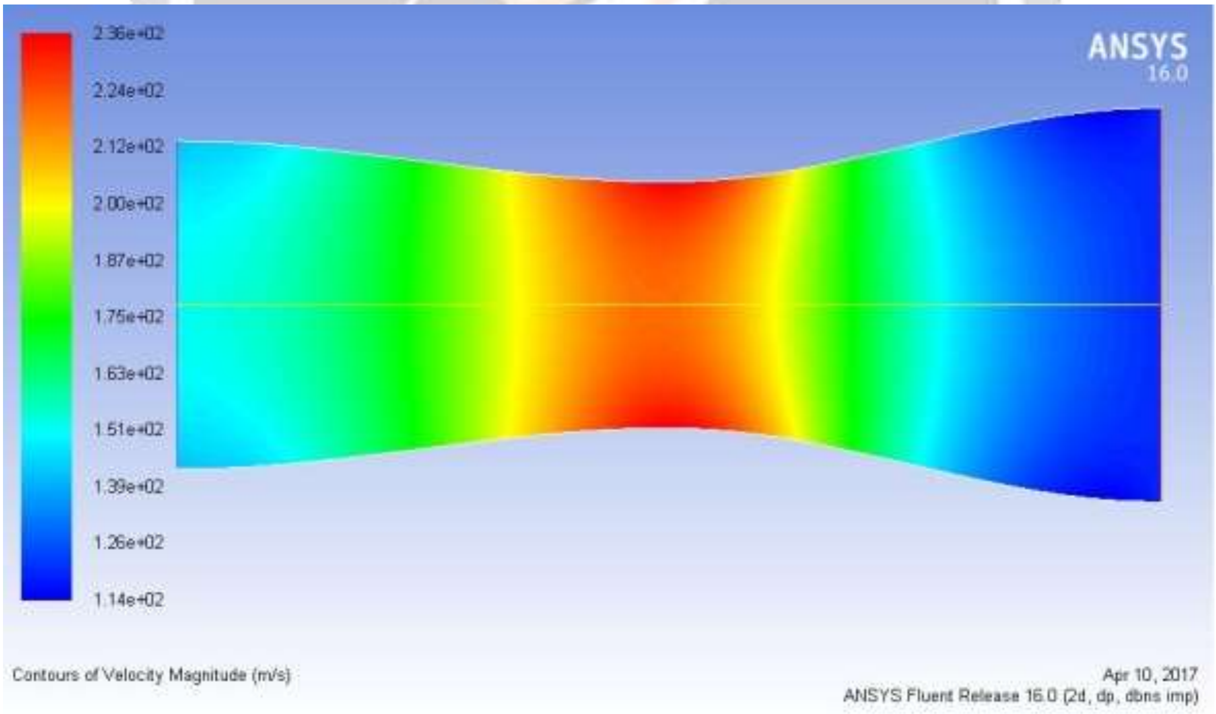


Fig -9: Scaled Residuals

Post Processing/Result

Velocity Variation

Velocity first increases to throat and then decreases . It is minimum at the inlet section and maximum at the throat and then decreases in the outlet section. Minimum velocity is 114.27 m/s. and maximum velocity is 236.21 m/s.



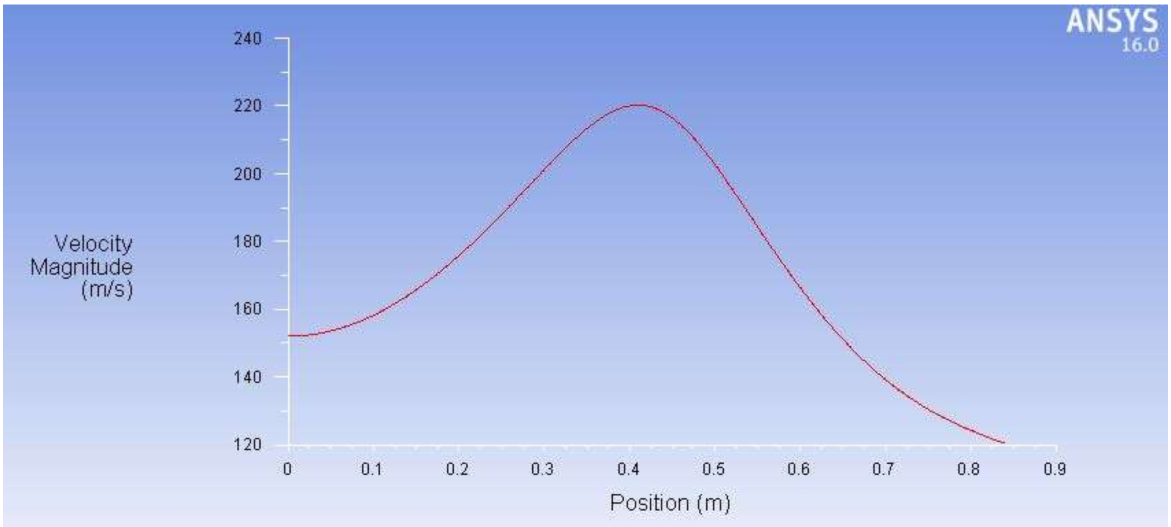


Fig -10. Velocity Contour and Graph (m/s)

Pressure Variation

Pressure is maximum at the outlet section and minimum at the throat. Maximum value of pressure is 221498.8 Pa and minimum value is 171234.3 Pa.

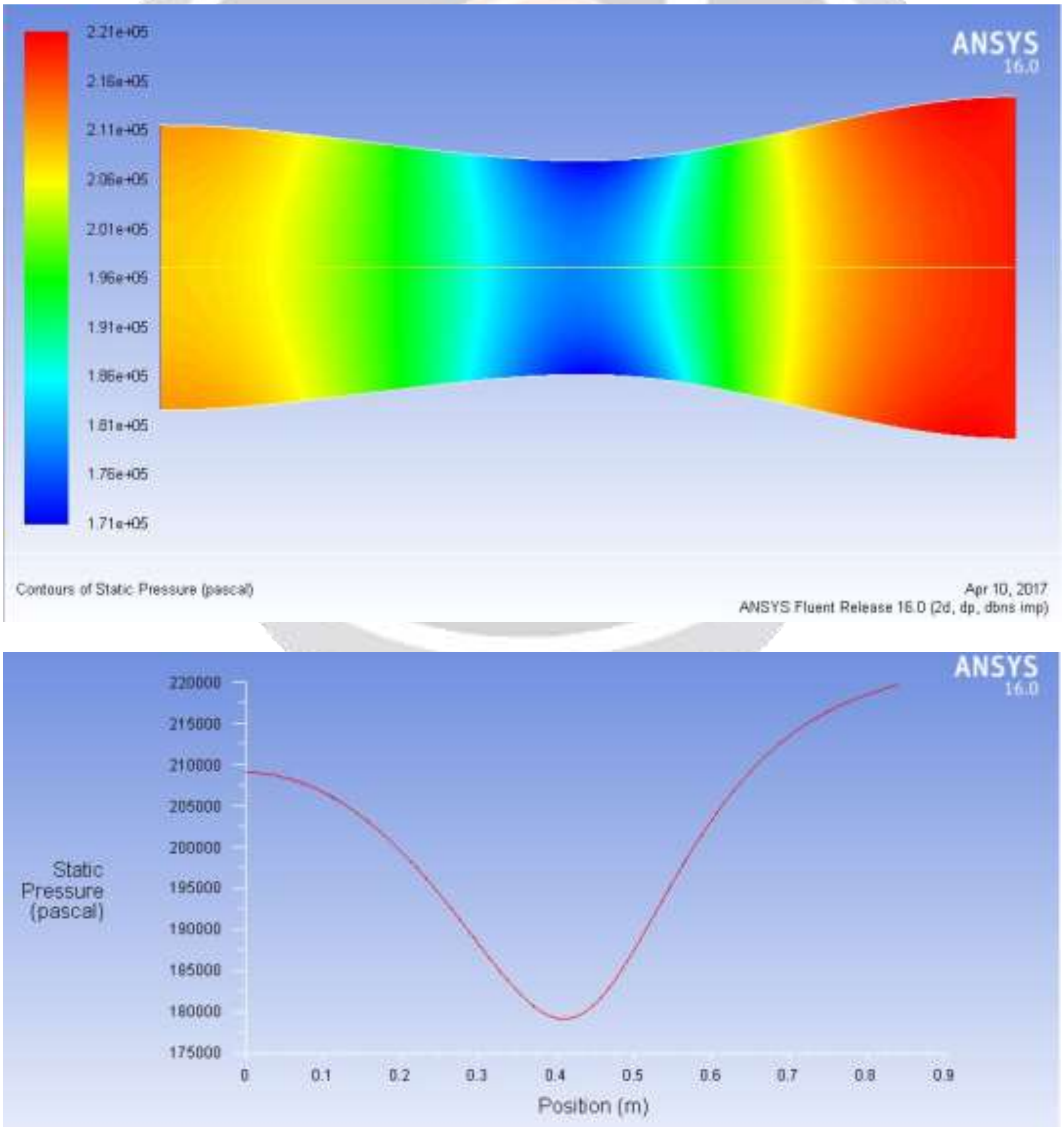


Fig -11. Pressure contour and Graph (Pa)

Case III : Pressure Ratio = 0.88

Table -7: Pre-processing Details

Boundary Conditions	Inlet Pressure = 238828.2 Pa Inlet Temperature = 300 *K* Outlet Pressure = 210168.8 Pa Outlet Temperature = 176.32 *K*

Table -8: Solver Details

Solution Control	Courant number = 5
Solution Initialization	Compute from = inlet
Run Calculation	Number of iterations = 5000

The solution was converged after 2688 iterations.

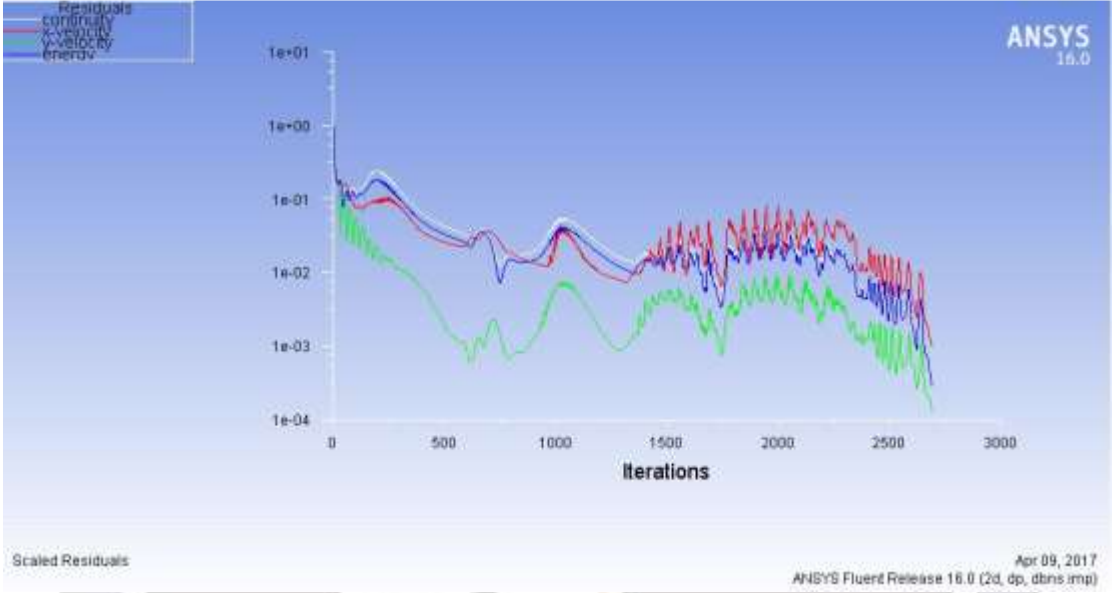
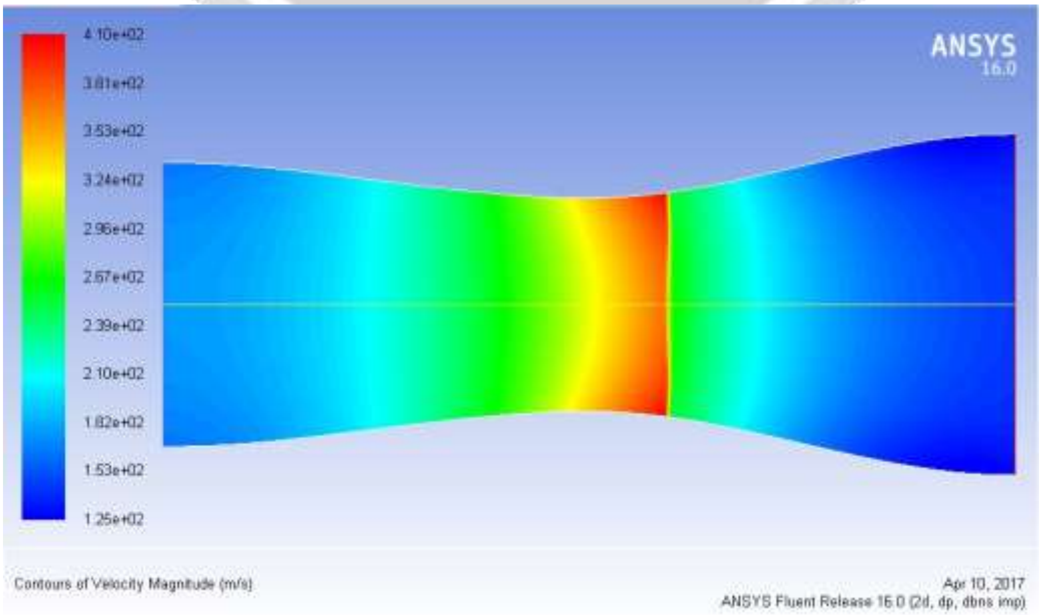


Fig -12. Scaled Residuals

Post Processing/Result

Velocity Variation

Minimum velocity is 124.82 m/s. and maximum velocity is 409.84 m/s. The normal shockwave is formed in the divergent section of the nozzle, the velocity abruptly decreases behind the shock.



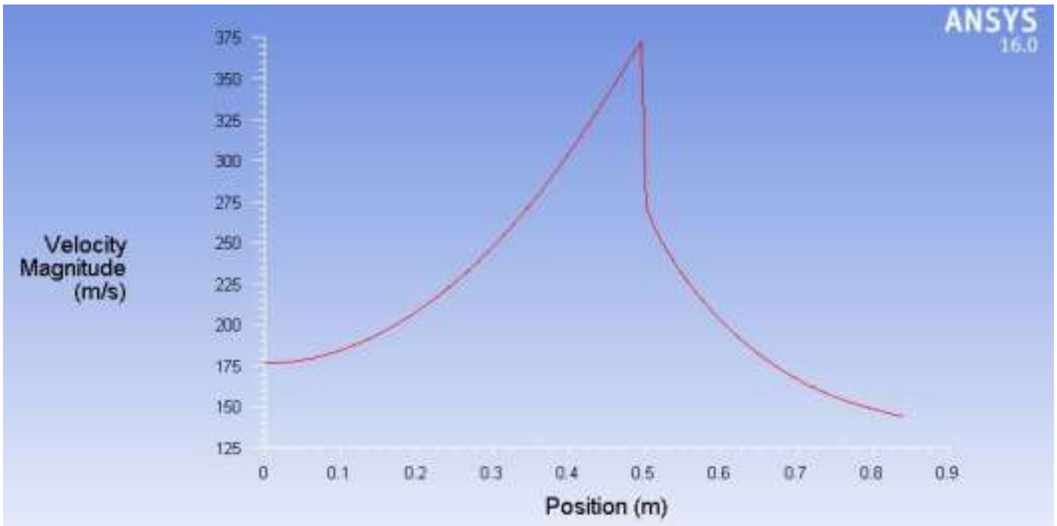


Figure 13. Velocity Contour and Graph (m/s)

Pressure Variation

Maximum value of pressure is 212131.6 Pa and minimum value is 78980.09 Pa. Due to the formation of normal shockwave in the nozzle the pressure abruptly increases behind the shock.

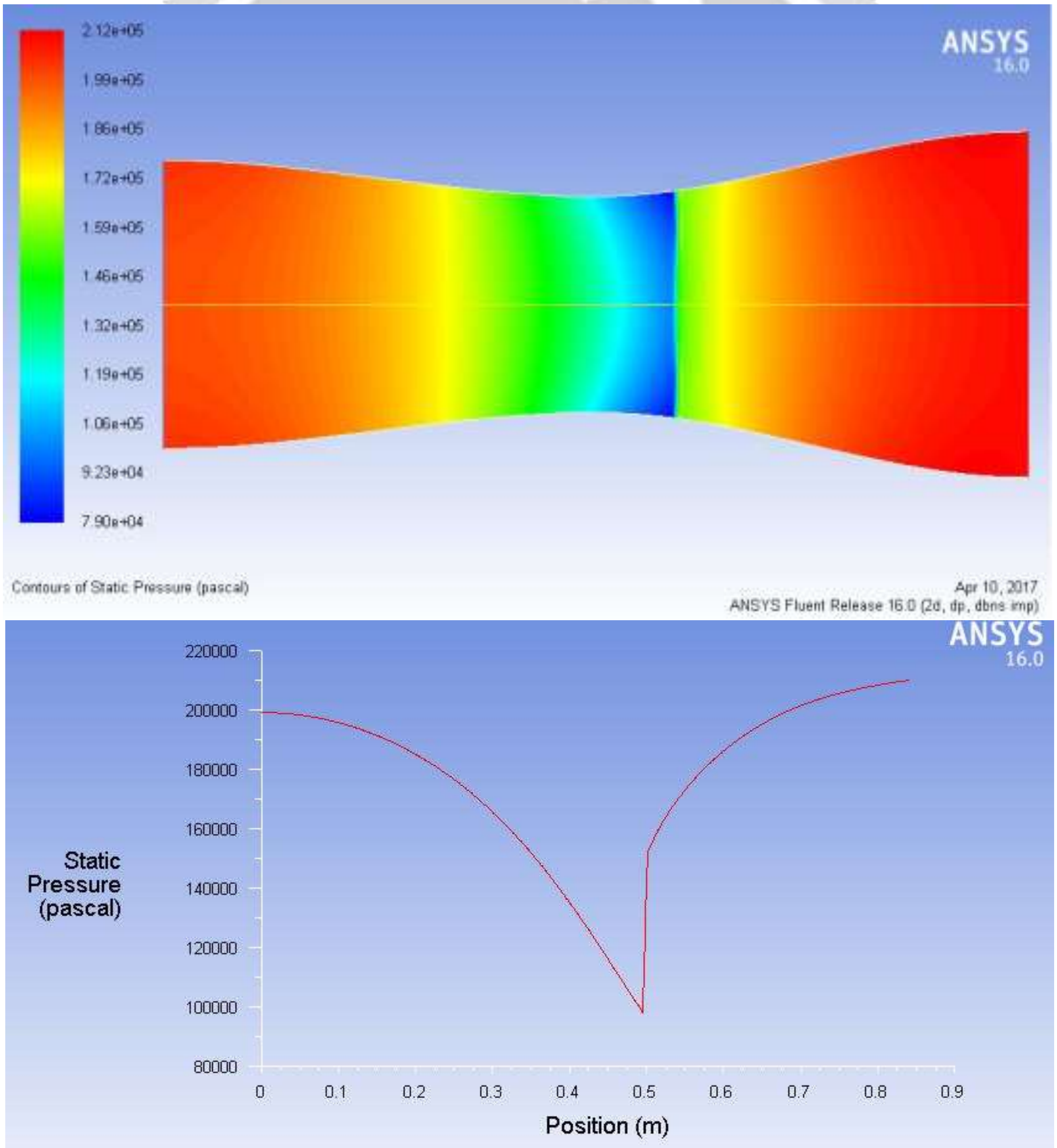


Fig -14. Pressure contour and Graph (Pa)

Case IV : Pressure Ratio = 0.80

Table -9: Pre-processing Details

Boundary Conditions	Inlet Pressure = 238828.2 Pa Inlet Temperature = 300 *K* Outlet Pressure = 191062.56 Pa Outlet Temperature = 176.32 *K*

Table -10: Solver Details

Solution Control	Courant number = 5
Solution Intialization	Compute from = inlet
Run Calculation	Number of iterations = 3000

The solution was converged after 1731 iterations.

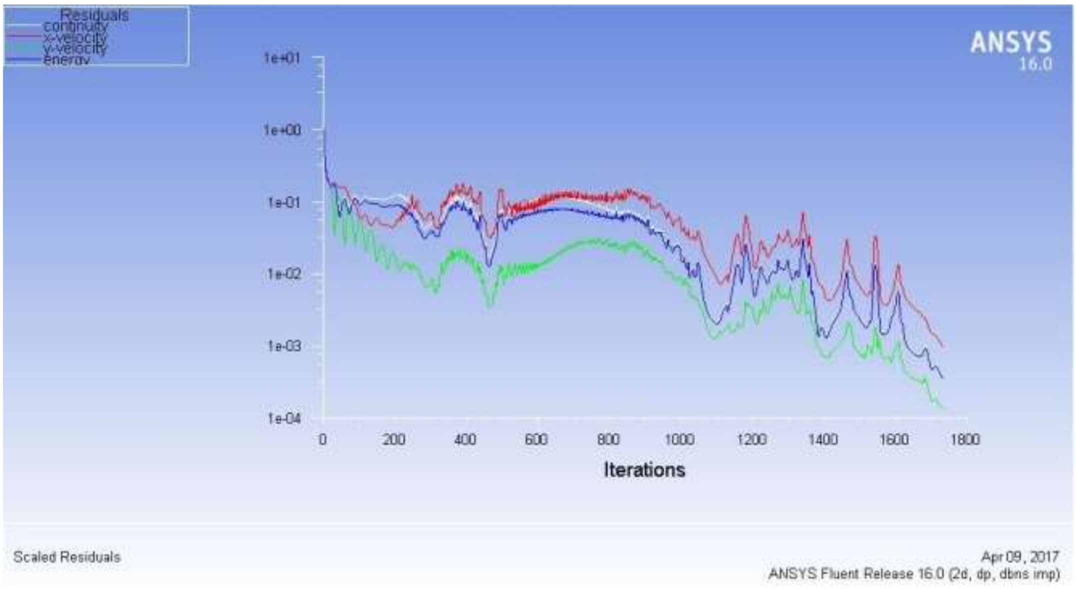
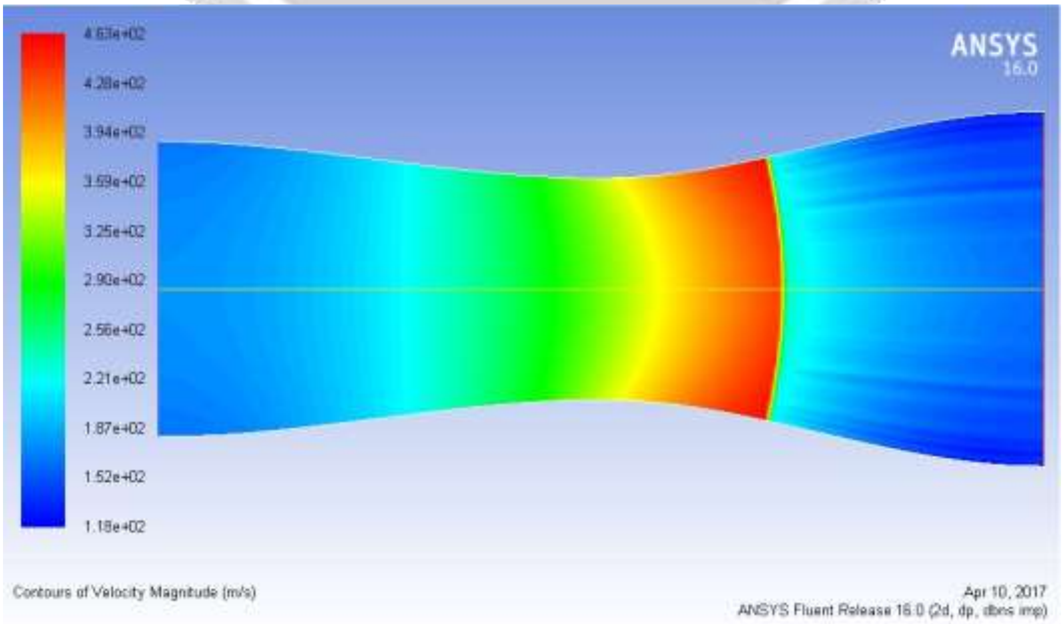


Fig -15. Scaled Residuals

Post Processing/Result

Velocity Variation

Minimum velocity is 117.55 m/s. and maximum velocity is 463 m/s. The position of normal shockwave is 0.5916 m from the nozzle inlet.



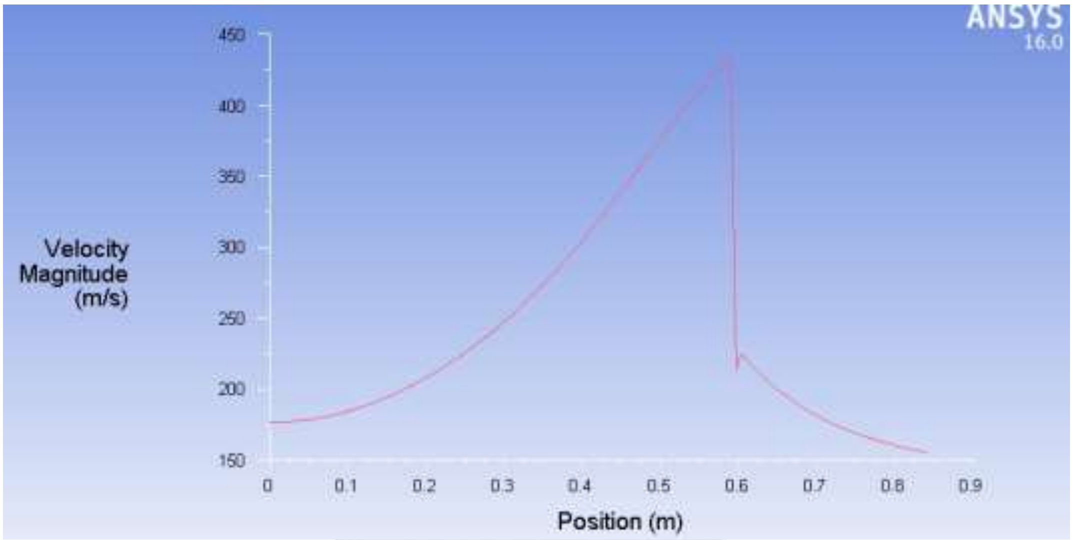


Fig -16. Velocity Contour and Graph (m/s)

Pressure Variation

Maximum value of pressure is 204644.1 Pa and minimum value is 55639.19 Pa.

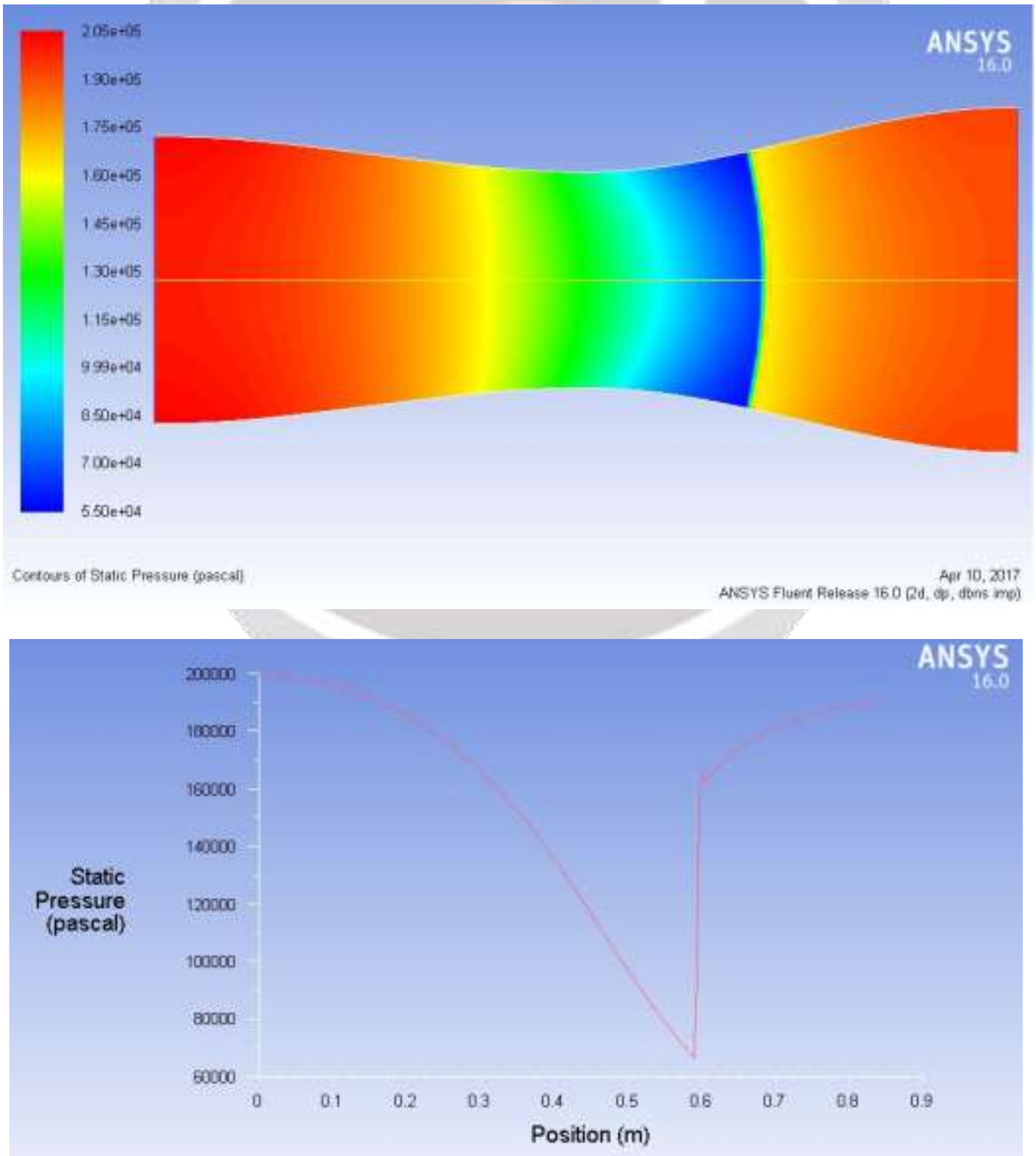


Fig -17. Pressure contour and Graph (Pa)

Case V : Pressure Ratio = 0.72

Table -11: Pre-processing Details

Boundary Conditions	Inlet Pressure = 238828.2 Pa Inlet Temperature = 300 *K* Outlet Pressure = 171956.3 Pa Outlet Temperature = 176.32 *K*

Table -12: Solver Details

Solution Control	Courant number = 5
Solution Initialization	Compute from = inlet
Run Calculation	Number of iterations = 3000

The solution was converged after 1943 iterations.

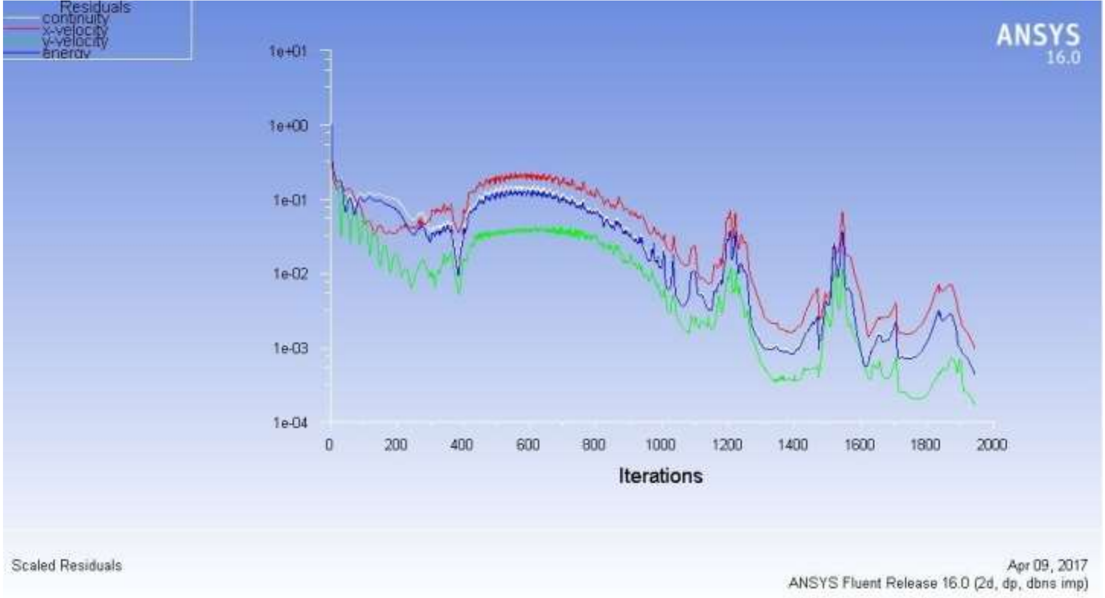
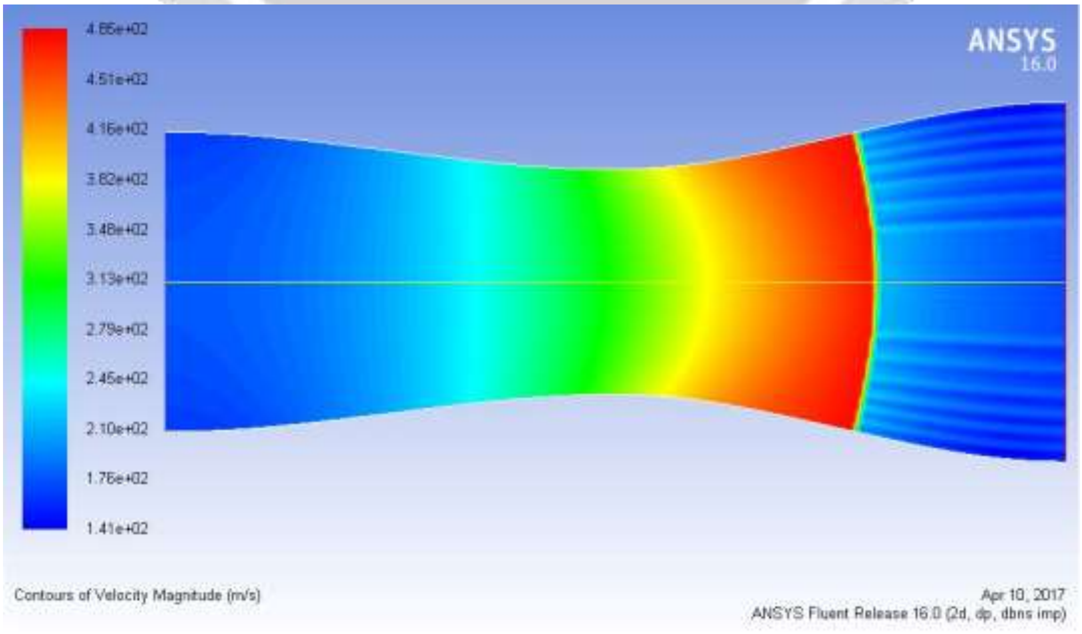


Fig -18. Scaled Residuals

Post Processing/Result

Velocity Variation

Minimum velocity is 141.43 m/s. and maximum velocity is 485 m/s. The position of normal shockwave is 0.6684 m from the nozzle inlet.



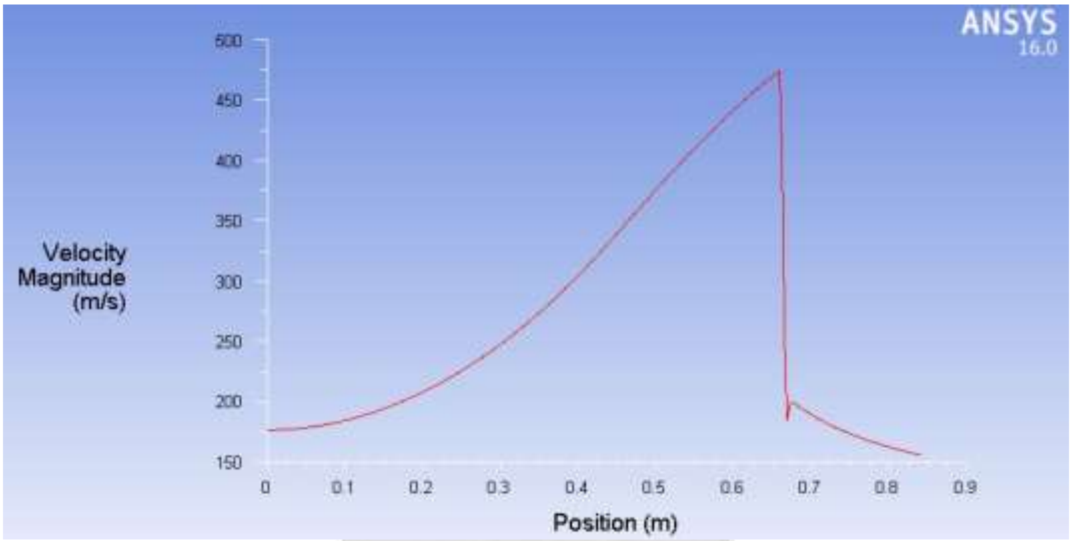


Fig -19. Velocity Contour and Graph (m/s)

Pressure Variation

Maximum value of pressure is 204644.1 Pa and minimum value is 45521 Pa.

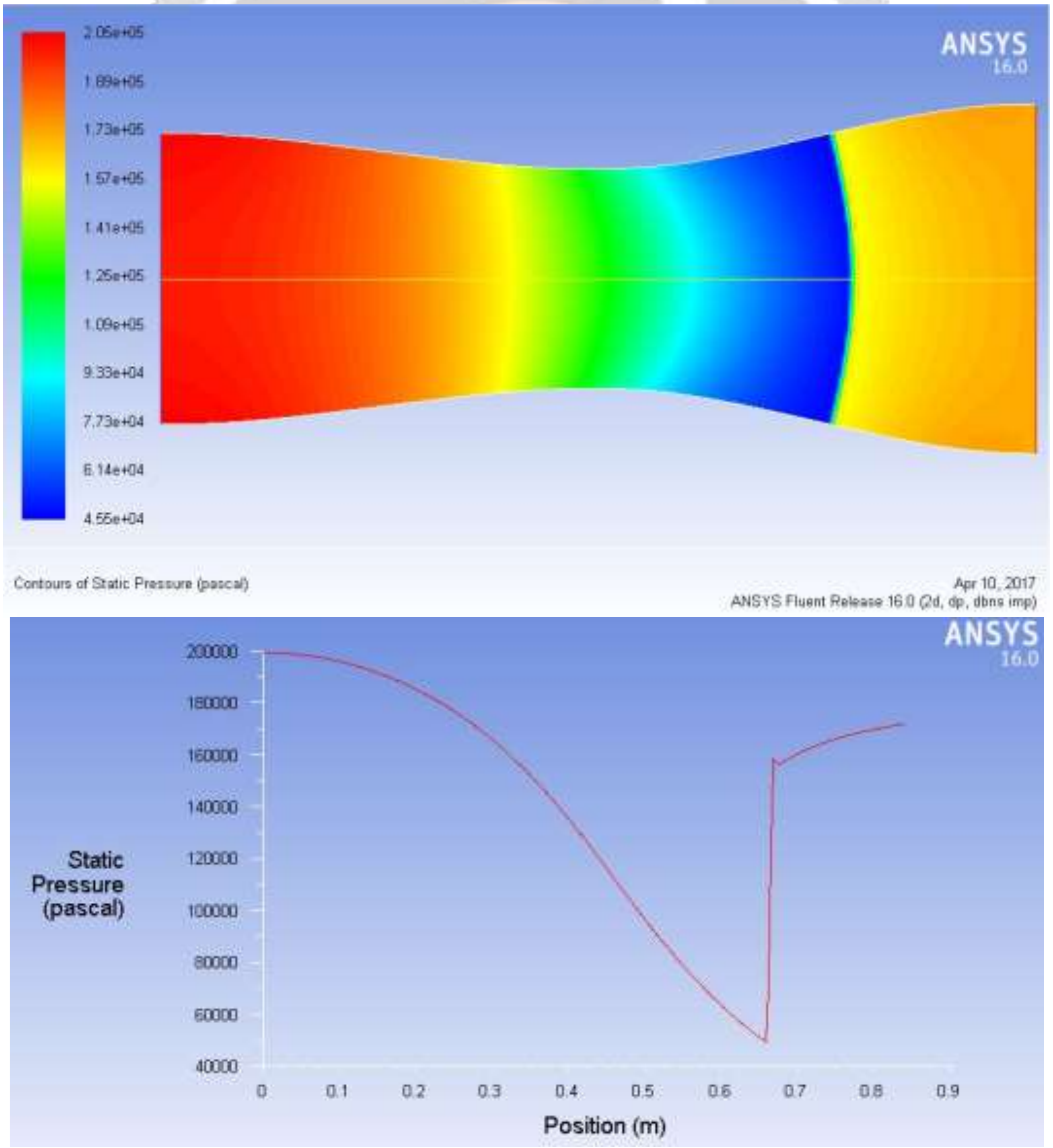


Fig -20. Pressure contour and Graph (Pa)

Case VI : Pressure Ratio = 0.64

Table -13: Pre-processing Details

Boundary Conditions	Inlet Pressure = 238828.2 Pa Inlet Temperature = 300 *K* Outlet Pressure = 152850.1 Pa Outlet Temperature = 176.32 *K*

Table -14: Solver Details

Solution Control	Courant number = 5
Solution Initialization	Compute from = inlet
Run Calculation	Number of iterations = 3000

The solution was converged after 1567 iterations.

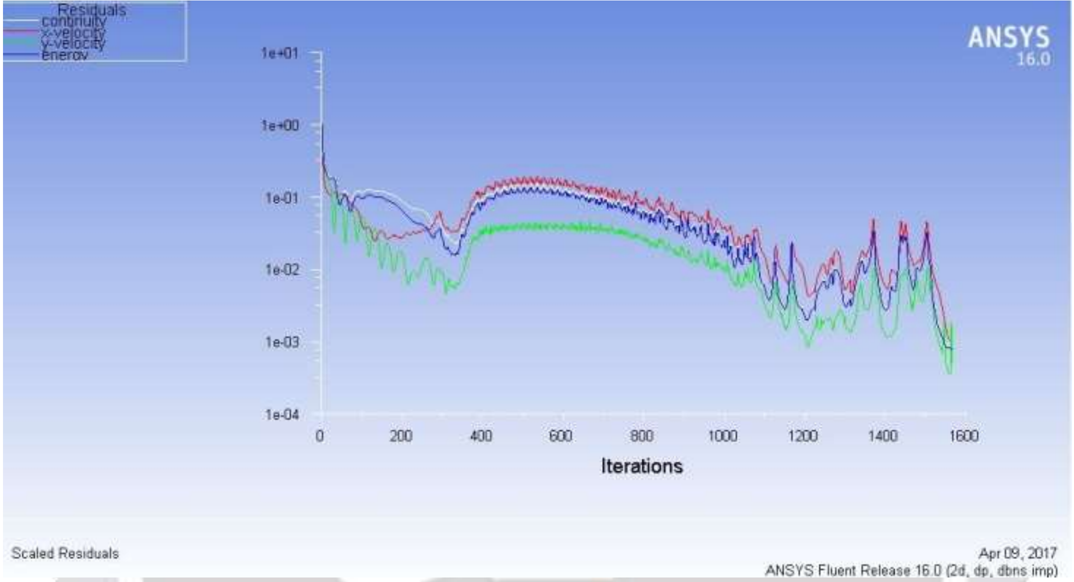
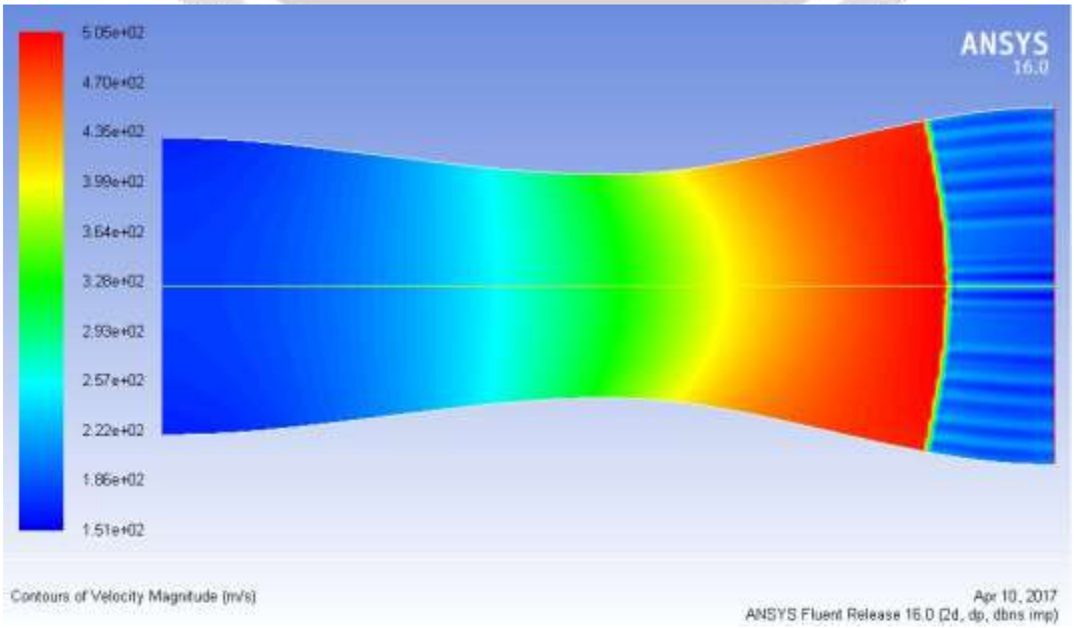


Fig -21. Scaled Residuals

Post Processing/Result

Velocity Variation

Minimum velocity is 151.02 m/s. and maximum velocity is 505.45 m/s. The position of normal shockwave is 0.7374 m from the nozzle inlet.



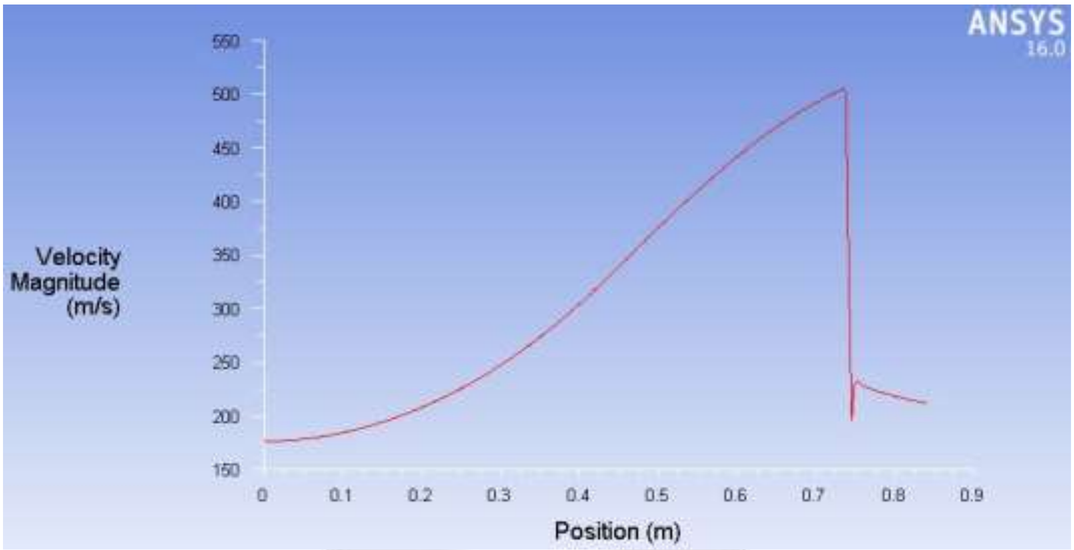


Fig -22. Velocity Contour and Graph (m/s)

Pressure Variation
Maximum value of pressure is 204644.2 Pa and minimum value is 37204.2 Pa.

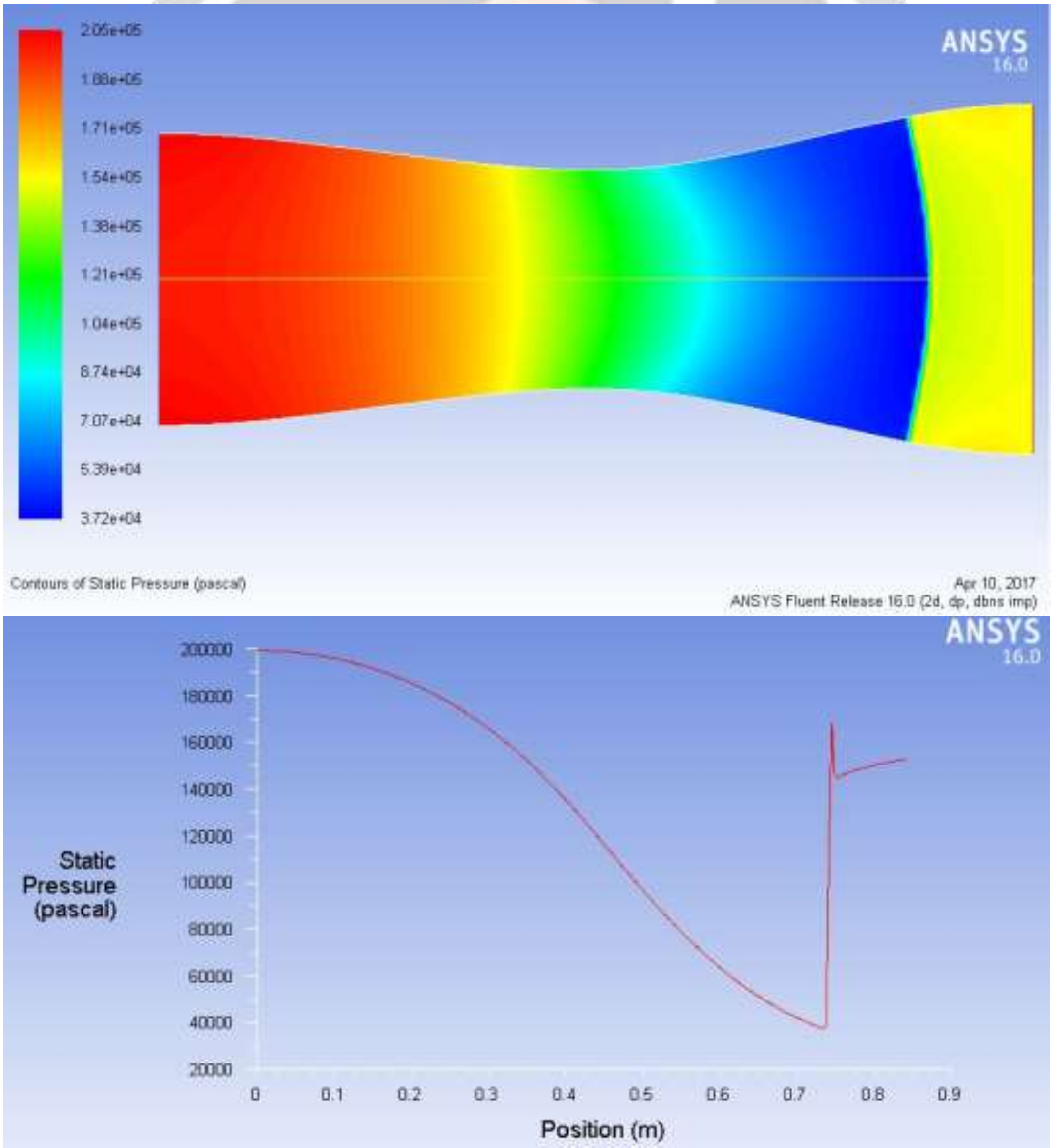


Fig -23. Pressure contour and Graph (Pa)

Case VII : Pressure Ratio = 0.56

Table -15: Pre-processing Details

Boundary Conditions	Inlet Pressure = 238828.2 Pa Inlet Temperature = 300 *K* Outlet Pressure = 133743.7 Pa Outlet Temperature = 176.32 *K*

Table -16: Solver Details

Solution Control	Courant number = 5
Solution Initialization	Compute from = inlet
Run Calculation	Number of iterations = 3000

The solution was converged after 931 iterations.

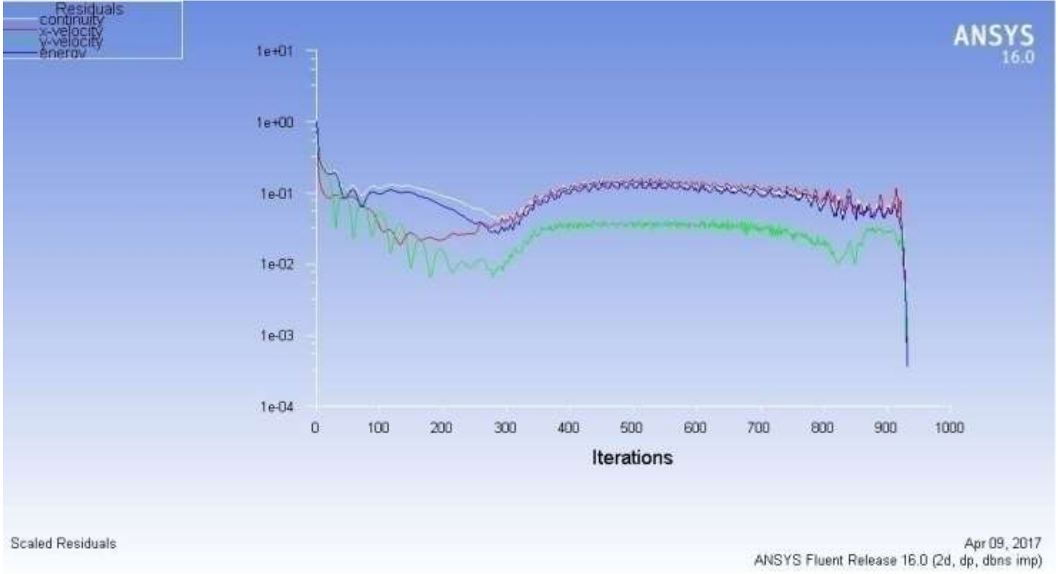
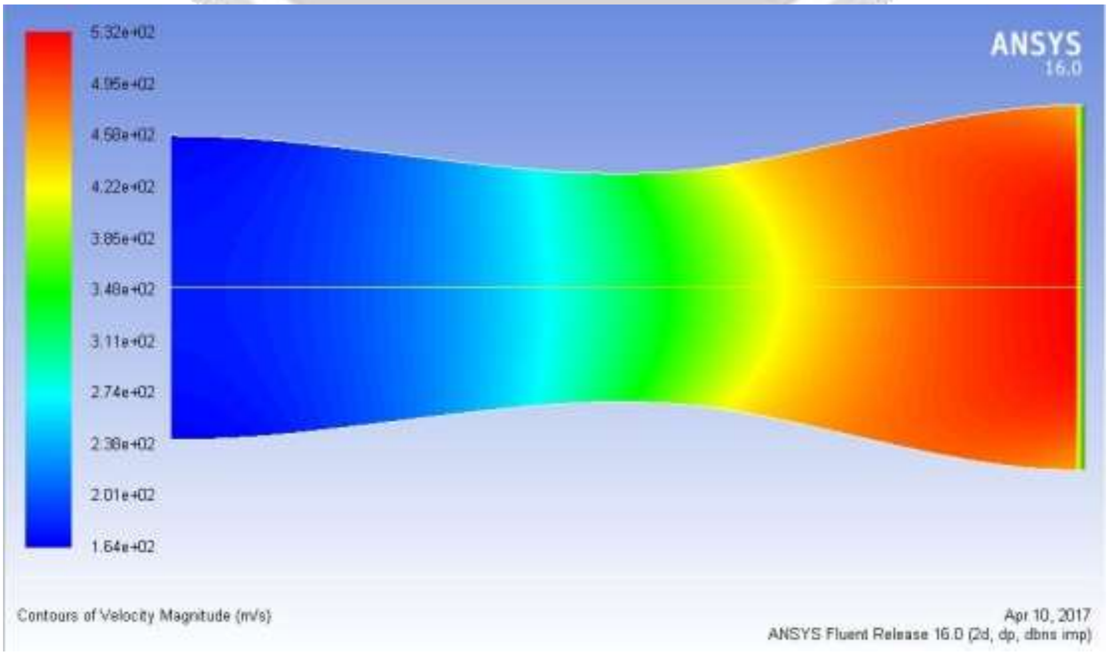


Fig -24. Scaled Residuals

Post Processing/Result

Velocity Variation

Minimum velocity is 163.93 m/s. and maximum velocity is 532.09 m/s. The position of normal shockwave is 0.8361 m from the nozzle inlet or the shockwave is formed at the nozzle outlet.



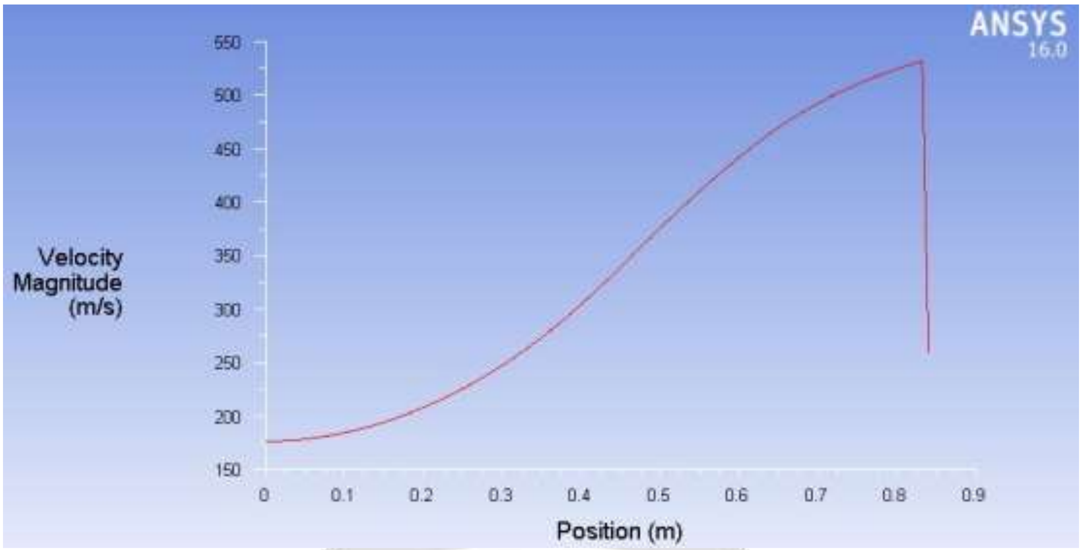


Fig -25. Velocity Contour and Graph (m/s)

Pressure Variation

Maximum value of pressure is 204625 Pa and minimum value is 28256.7 Pa.

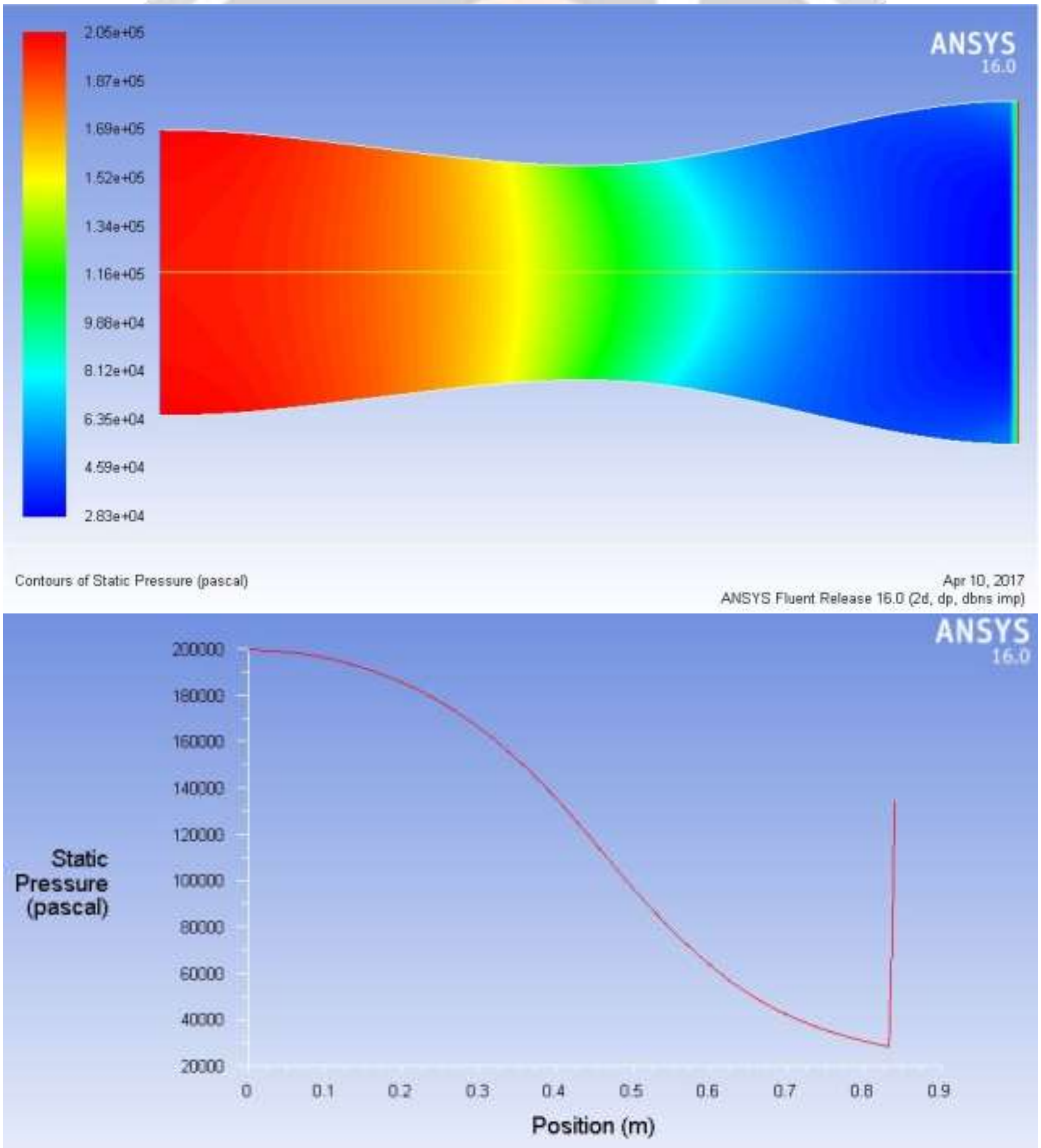


Fig -26. Pressure contour and Graph (Pa)

4. CONCLUSION

By this paper we have explained the basic concepts connected with De-Laval nozzle. Through this study and analysis, we have found out the position of normal shockwave in the divergent section of De-Laval Nozzle with the help of Computational Fluid Dynamics values. The above are discussed in detail in table below.

Table -17: Determination of Shockwave in Nozzle various pressure ratio

Pressure Ratio	Position of Normal Shockwave in the divergent section (m)
0.88	0.4972
0.86	0.5282
0.84	0.5523
0.82	0.5745
0.80	0.5916
0.78	0.6151
0.76	0.6303
0.74	0.6555
0.72	0.6684
0.70	0.6849
0.68	0.7053
0.66	0.7194
0.64	0.7374
0.62	0.7595
0.60	0.7858
0.58	0.8128
0.56	0.8361

The graphs of Pressure, Velocity, Mach Number with different pressure ratios have been plotted below

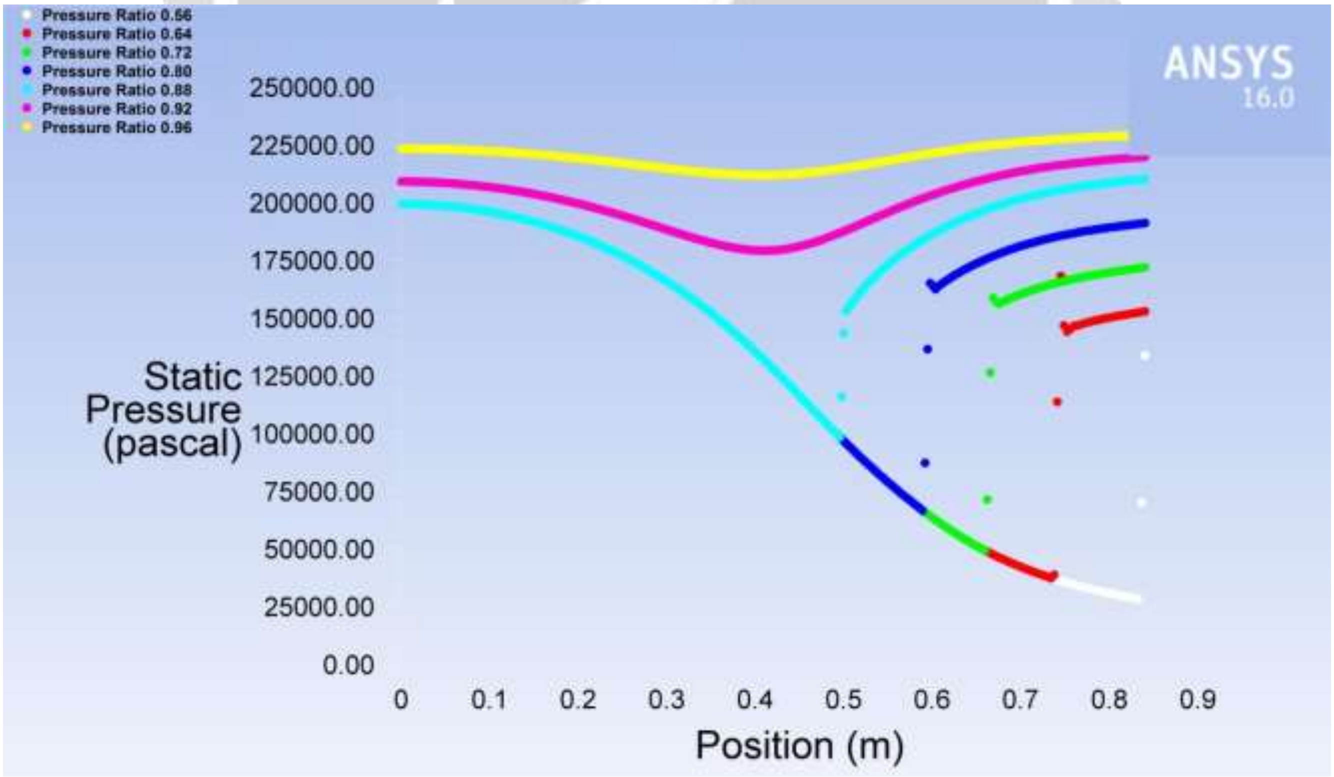


Fig -30. Pressure Graph for different pressure ratio.

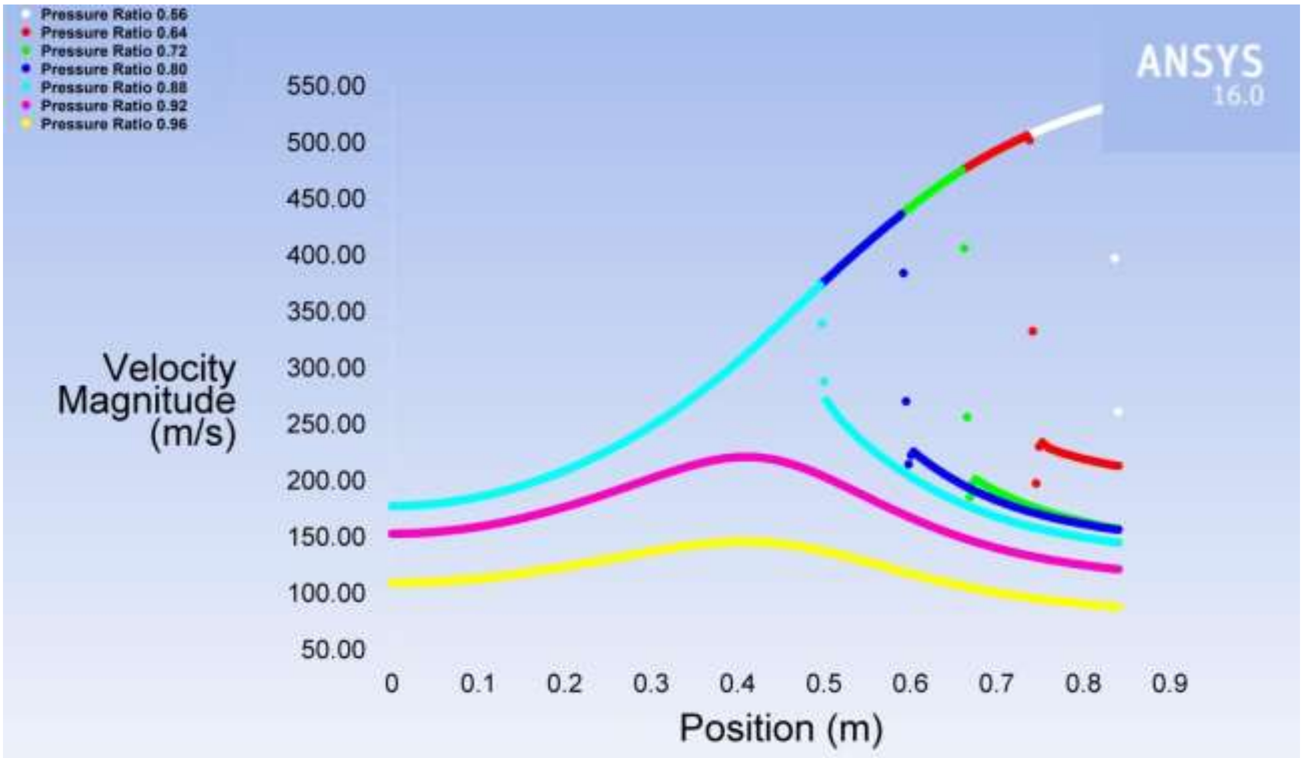


Fig -31. Velocity Graph for different pressure ratio.

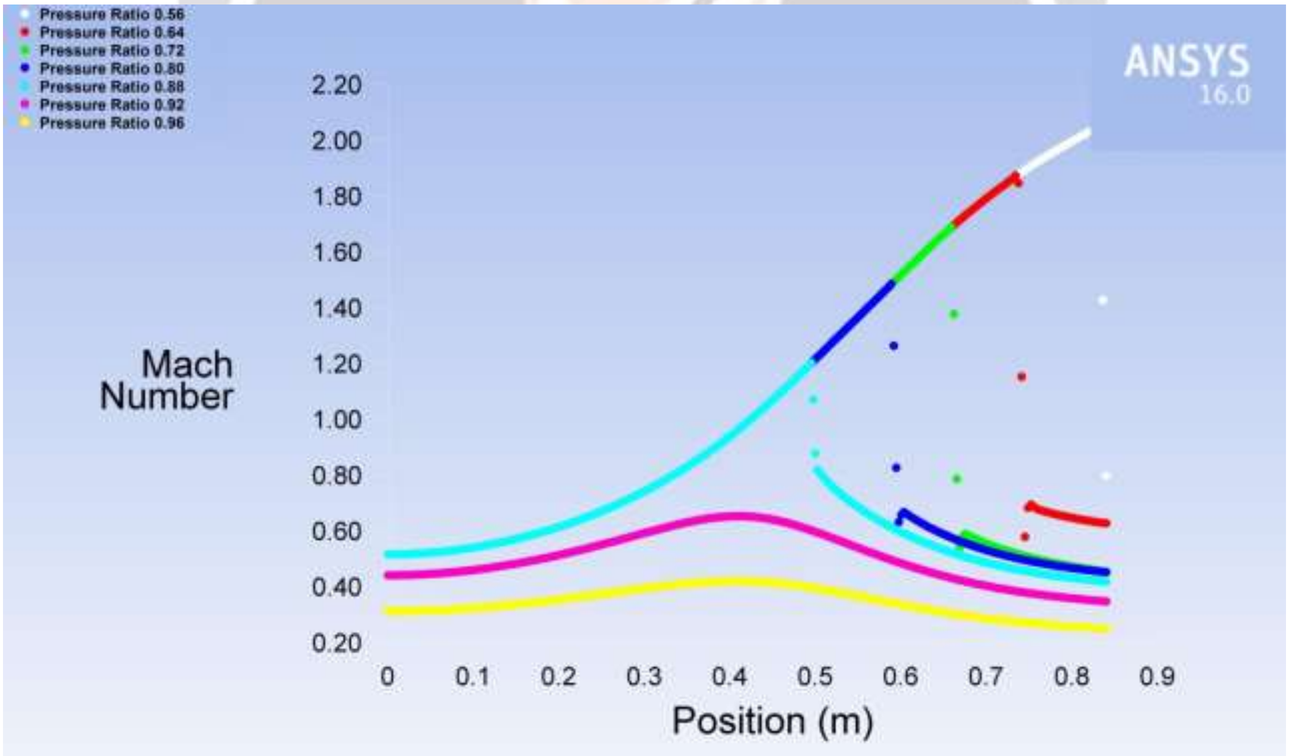


Fig -32. Mach No. Graph for different pressure ratio.

5. ACKNOWLEDGEMENTS

We thank Mr. S.K Rana and Mr. Rahul Kumar without whose help this project would not have been possible.

6. REFERENCE

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