MODELING AND SIMULATION OF SUPERSONIC SEPARATOR USED IN SUBSEA GAS PIPELINE SYSTEMS

Submitted by

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MODELING AND SIMULATION OF SUPERSONIC SEPARATOR USED IN SUBSEA GAS PIPELINE SYSTEMS

A thesis submitted in partial fulfilment of the requirements for the Degree of

Master of Technology
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Submitted By

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Under the guidance of

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Approved

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College of Engineering
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UNIVERSITY OF PETROLEUM AND ENERRGY STUDIES, DEHRADUN

BONAFIDE CERTIFICATE

Certified this titled ***"Modeling and Simulation of Supersonic Separator used in Subsea Gas Pipeline Systems"*** is the bonafide work of **Mr. Lokesh Kumar Mylapilli (R150213017)** who carried out the work under my supervision. Certified further that to the best of my knowledge the work reported here in does not form part of any other thesis or dissertation on the basis of which a degree or award was conferred on an earlier occasion on this or any other candidate.

Dr. GURUNADH VELIDI

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ABSTRACT

The supersonic separator is unique technology which gained market acceptance. The usage in subsea systems have been increasing extensively. The conversion of kinetic energy into pressure energy at the diffuser makes this device more special. The pressure recovery technique helps the system to use near the well head where the pressure is drastically reduced to limited range. In this project the Numerical study of supersonic separator is done using the computational Fluid Dynamics package FLUENT. The simulations are run using three different fluids, air, methane and natural gas given the same boundary conditions and initial physical parameters. The Redlich – Kwong real gas equation and standard k-Ɛ turbulence model is employed. The result shows that the shock formed in the nozzle of the supersonic separator is depending on the density of the fluids, the lighter the fluid the closer the shock position to inlet. The Pressure and temperature variation is also high in low density fluids.

ACKNOWLEDGEMNTS

I would like to express my deep gratitude towards Dr. Gurunadh Velidi Assistant professor, University of Petroleum and Energy Studies, for his continuous support and guidance throughout the project.

I wish to show my gratitude to my department faculty Mr. Adarsh Kumar Arya, Mr. Balachander Singhan, Mr. Santosh Kumar Kurre, Mr. Ramesh for their guidance and suggestion in completing the thesis.

I feel immense delight to acknowledge the staff of University of Petroleum and Energy Studies, Dehradun for their support and care they provided throughout the work.

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NOMENCLATURE

a	Constant for attractive potential of molecules
b	Constant for volume
C_μ	Constant
D	Diameter
D_1	Inlet diameter
D_{cr}	Throat diameter
E	Total Energy
k	Turbulent kinetic energy
L	Convergent length
p	Static pressure
p_c	Critical pressure
q_j	Heat flux
R	Gas constant
R_e	Reynolds number
T	Temperature
T_c	Critical temperature
u	Mean velocity
u_x	X axis velocity
u_y	Y axis velocity
Vm	Gas molar volume
x	Arbitrary distance
X_m	Relative coordinate
ϵ	Turbulent dissipation rate
τ_{ij}	Viscous stress
δ_{ij}	Kronecker delta

1.0 INTRODUCTION

Natural gas which is transmitted in subsea pipelines need to be dehydrated to ensure smooth operation of gas transmission. The liquid water in pipelines may condense and accumulate at low points along the pipeline reducing its flow capacity. [2] The mixture of liquid and gas might cause liquid hammering in the pipelines and may damage the equipment's especially the rotating equipment's.

In order to overcome the transmission problems in pipelines a supersonic separator has been introduced. The supersonic separator processes the natural gas for condensation and separating water from heavier hydrocarbons.

1.1 Supersonic Separator

This supersonic separator combines the thermo-dynamics, fluid-dynamics and aero-dynamics to create an advanced gas conditioning process. Condensation and separation takes place at supersonic velocity that's the key achievement of this supersonic separator. This feature helps in reduction of both operating cost and capital cost.

The supersonic separator shown in the figure 1; works on the principles of a) gas expansion, b) cyclone separation and c) re- compression. [3]

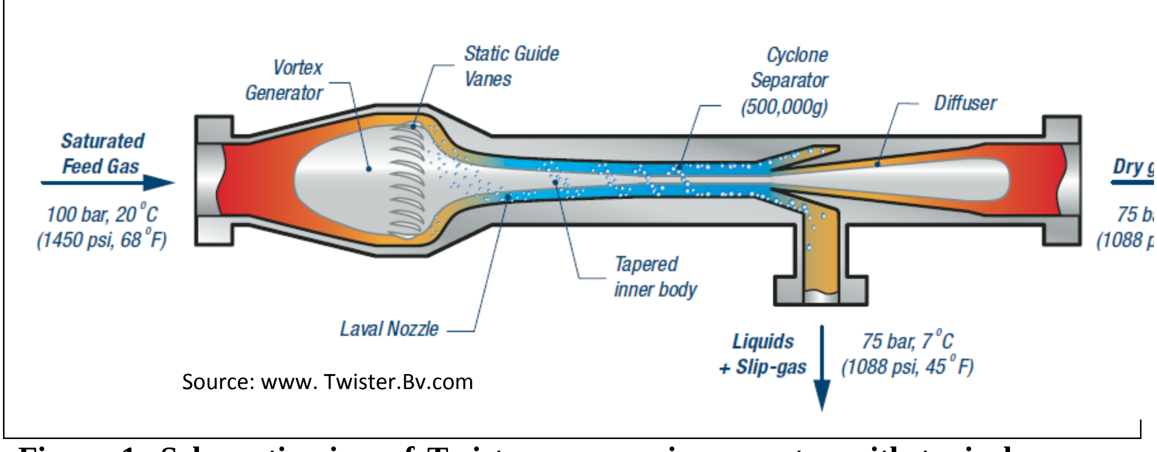


Figure 1: Schematic view of Twister supersonic separator with typical process conditions.

The basic working concepts of the supersonic separator from figure 1 are:

- A high vorticity concentric swirl is generated by the guide vanes at the inlet.

- Laval Nozzle expands feed gas which helps in reaching subsonic velocity to supersonic velocity.
- Low temperature and Pressure are obtained which results in formation of a mist of water and hydrocarbon condensation droplets.
- The swirling motion generated forces the droplets to the walls.
- The cyclone separator removes the droplets
- The diffuser moderates downs the streams and recoups 80-85% of the remaining free pressure.[10]

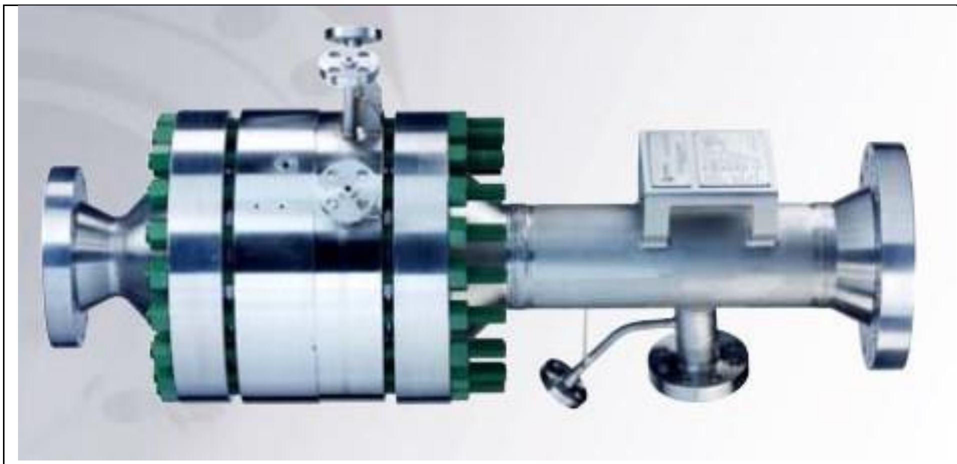
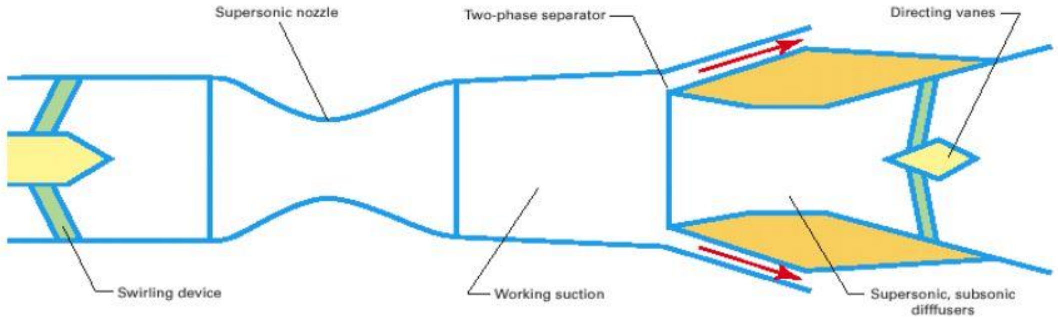


Figure 2: Twister Model

There are other types of supersonic separators known as 3S Separator. Although the physical appearances change the working principle is same for both the devices.



Source: www. Twister.Bv.com

Figure 3: Schematic of a 3S Separator

The 3S (Super Sonic Separation) Separator came into industrial application in the mid of July 2007. The technology also uses the same working principles but the swirl generator and the body design are varied compared to twister device.

1.2 Comparison of Supersonic Separator with JT Expansion Devices

Joule-Thompson expansion is describes as the change of temperature of fluid either gas or liquid when it is passed through a valve and no heat exchanged with the surrounding environment.

A Joules – Thomson (JT) expansion device consists of

- A gas exchanger
- Methanol injector
- JT valve
- Cold separator
- Control system

High Pressure gas is passed through the exchanger for cooling. Methanol is injected to prevent hydrate formation and the raw gas passes through the JT valve. Expansion is caused due to the pressure drop and significant temperature reduced due to JT effect.

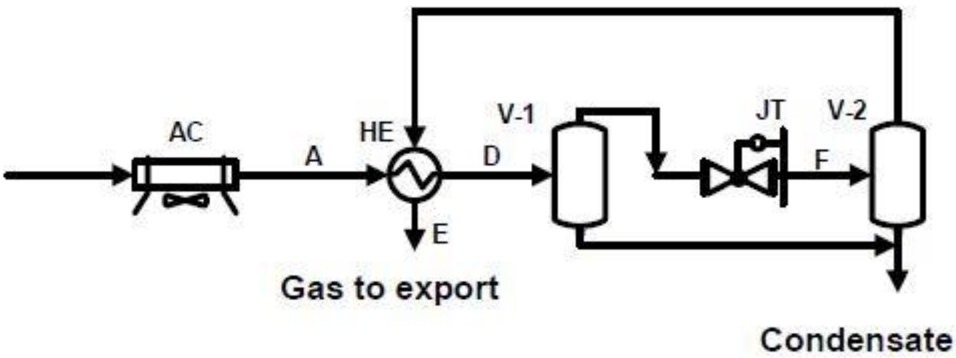


Figure 4: Typical Process setup of JT expansion Device

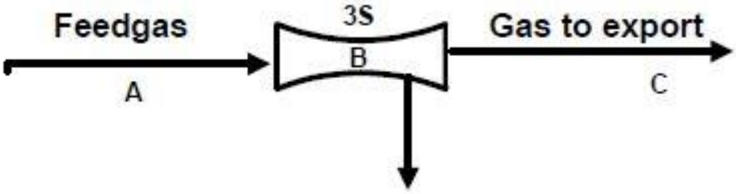


Figure 5: Typical Process setup of 3S separator

By observing the process setups we can clearly identify the complex arrangement of JT expansion device compared to 3S of Twister devices. The supersonic separator eliminates the use of injectors, valves and cold separators. The residence time of gas in supersonic separator is only milliseconds [10]. This ensures that the formation of hydrates is not possible due to its low residence time; this eliminates the use of external chemical injection system.

1.3 Efficiency Comparison of Twister and JT

For efficiency comparison, the thermodynamics of both the devices are compared. For example for same operating conditions of Inlet pressure of 100 bar and temperature 40^0C and the pressure drop of 30%, the Twister uses isentropic (No entropy change) expansion achieving 60^0C cooling with 30bar pressure drop whereas the JT expansion device uses isenthalpic (no enthalpy change) expansion process which limit the cooling with available pressure drop. Due to this a separate dehydrate system at the upstream of the device mounted or chemical injection system is added to the JT expansion device.

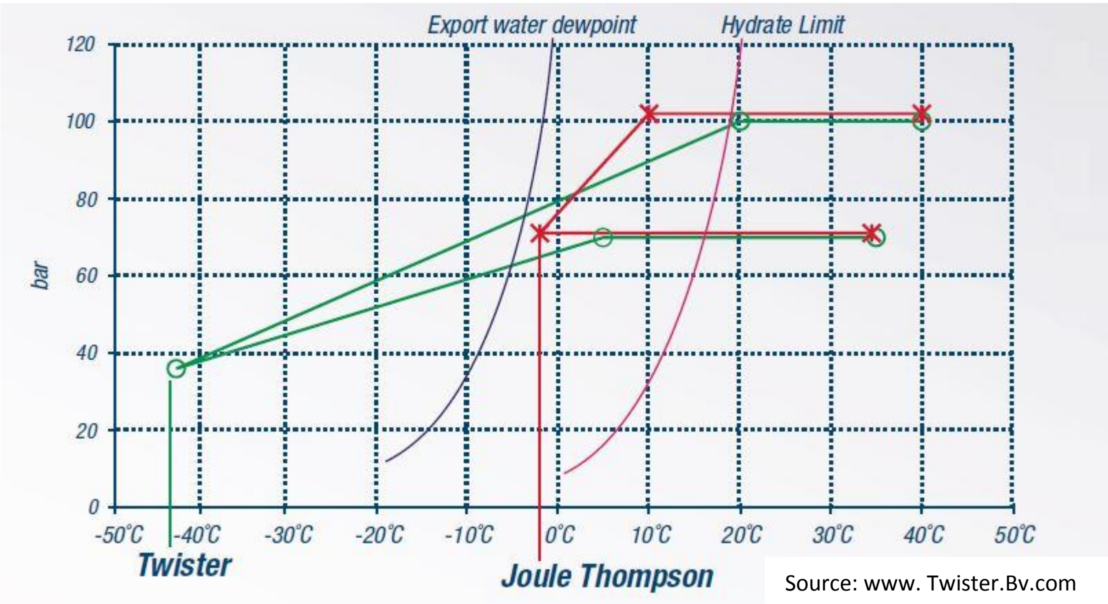
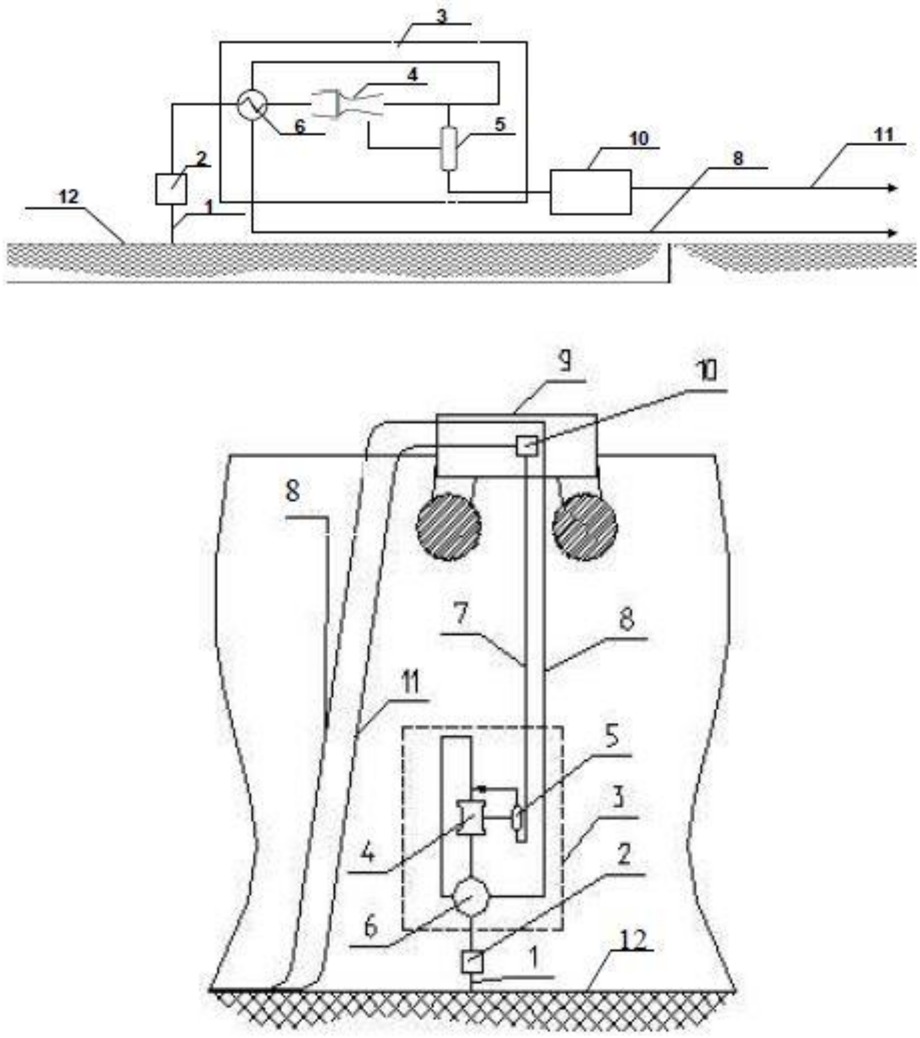


Figure 6: Twister and JT device efficiency comparison

1.4 Sub-Sea Gas Processing using supersonic separator

Most of the offshore platforms work on the maximum pressure limit of 100 bar due to platform safety and personnel safety. Sometimes the pressures from the well-heads, may cross the limit specified. To reduce the pressure to be within the limit usually a JT valve is fixed. By Replacing the JT valve with supersonic separator, will have simultaneous solutions for many problems like pressure reduction, condensate extraction, and gas dehydration.

A scheme of utilizing supersonic separator in subsea processing for condensate extraction is shown below.



1. Well, 2. Well – Head, 3. Condensate Extraction facility, 4. Supersonic separator, 5. Gas-liquid separation, 6. Heat – Exchanger, 7, 11. Pipeline for condensate transportation, 8. Gas – Pipeline for purified gas, 9. Offshore Platform, 10. Facility for preparing condensate for transportation, 12. Sea land.

Figure 7: A possible scheme of Subsea processing for condensate using supersonic separator

1.5 Benefits of Supersonic separator

The benefits of the supersonic separator are as follows:

- The absence of moving parts.
- Low operating cost and capital cost
- No impact on environment
- Routine Maintenance is not required
- Greater Portability due to small size
- Reduced Installation and Handling costs
- Supports unmanned operation
- Since the separator is closed system, no emissions are seen
- Chemical usage is nullified i.e., no usage of chemicals like Glycol and Methanol.

1.6 Industrial Applications:

The supersonic separator has wide applications in oil and gas industry. It is used for dehydration (water Dew pointing), hydrocarbon Dew pointing, and Natural gas liquids recovery. It also prevents the formation of hydrates and eliminates the use of inhibitors and regeneration systems (adding Glycol, Methanol), because of fluids less residence time in the device. [3]

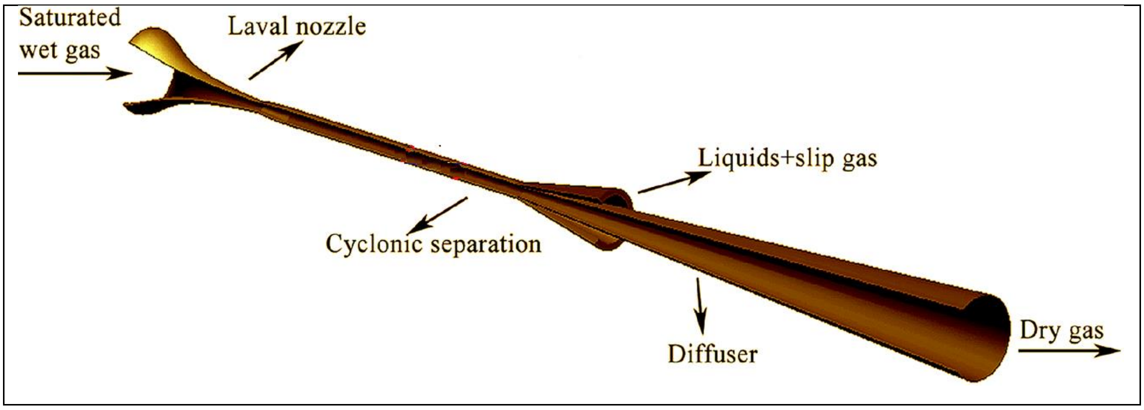


Figure 8: Typical Supersonic separator used in industries.

1.7 Computational Fluid Dynamics

The Computational Fluid Dynamics (CFD) is a computing application which is used to describe and simulate fluid dynamic phenomena. CFD also is an engineering method for simulating the performance of systems, processes and equipment comprising flow of gases and liquids, chemical reactions, heat and mass transfer and related physical phenomena. Fluids flows can be analyzed without leading to the real test by utilizing the numerical methodology; subsequently it can decrease the time and expense for trial based examination. [9]

1.8 Objectives

1. To model the supersonic separator

2. To study the shock wave produced in the nozzle with different working fluids.

3. To study the behaviour of sweet and sour natural gas in the separator.

1.9 Scope of thesis

Numerical Simulation was conducted to predict and analyze fluid behavior across a supersonic separator. Axisymmetric modelling was done to identify the shock wave position. Different fluids are transferred through the model and the shock wave location is identified. The physical parameters change after the shock generation is studied. The natural gas of both sweet and sour are transferred into the separator and the physical parameter change is studied.

3.0 METHODOLOGY:

This Thesis is based on numerical analysis where a computational simulation is carried out instead of an actual experiment on a prototype. The CFD method was used as a tool to predict the flow behaviour of fluids passing in the supersonic separator.

Before the simulation process started, several information regarding the supersonic separator need to be determined. Among the information are;

- Prototype parameters and geometry,
- Type of process fluid, operating condition,
- Types of flow pattern and
- Type of Governing equation to be used to solve the numerical problems.

Later, the model is constructed in GAMBIT and imported to solver. The type of flow model and the approaches must be selected depends on the problem to be solved.

The overall all project time is calculated and shown in the below figure.

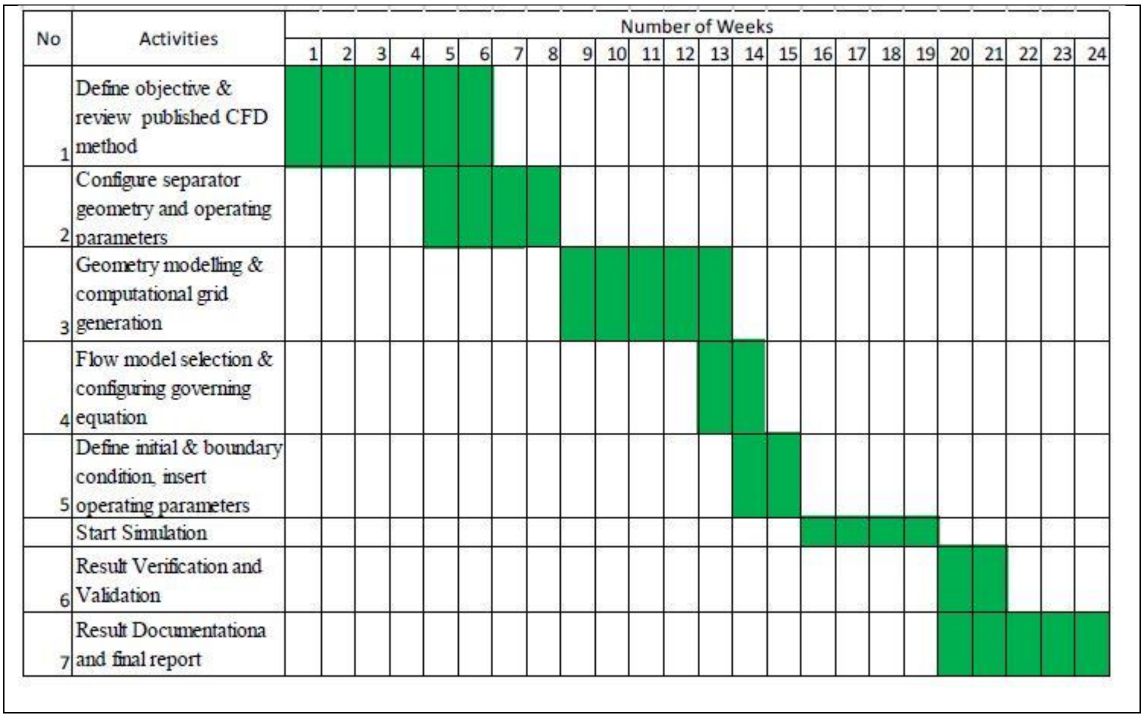


Figure 9: Project Schedule

In this thesis the methodology employed is shown in the figure

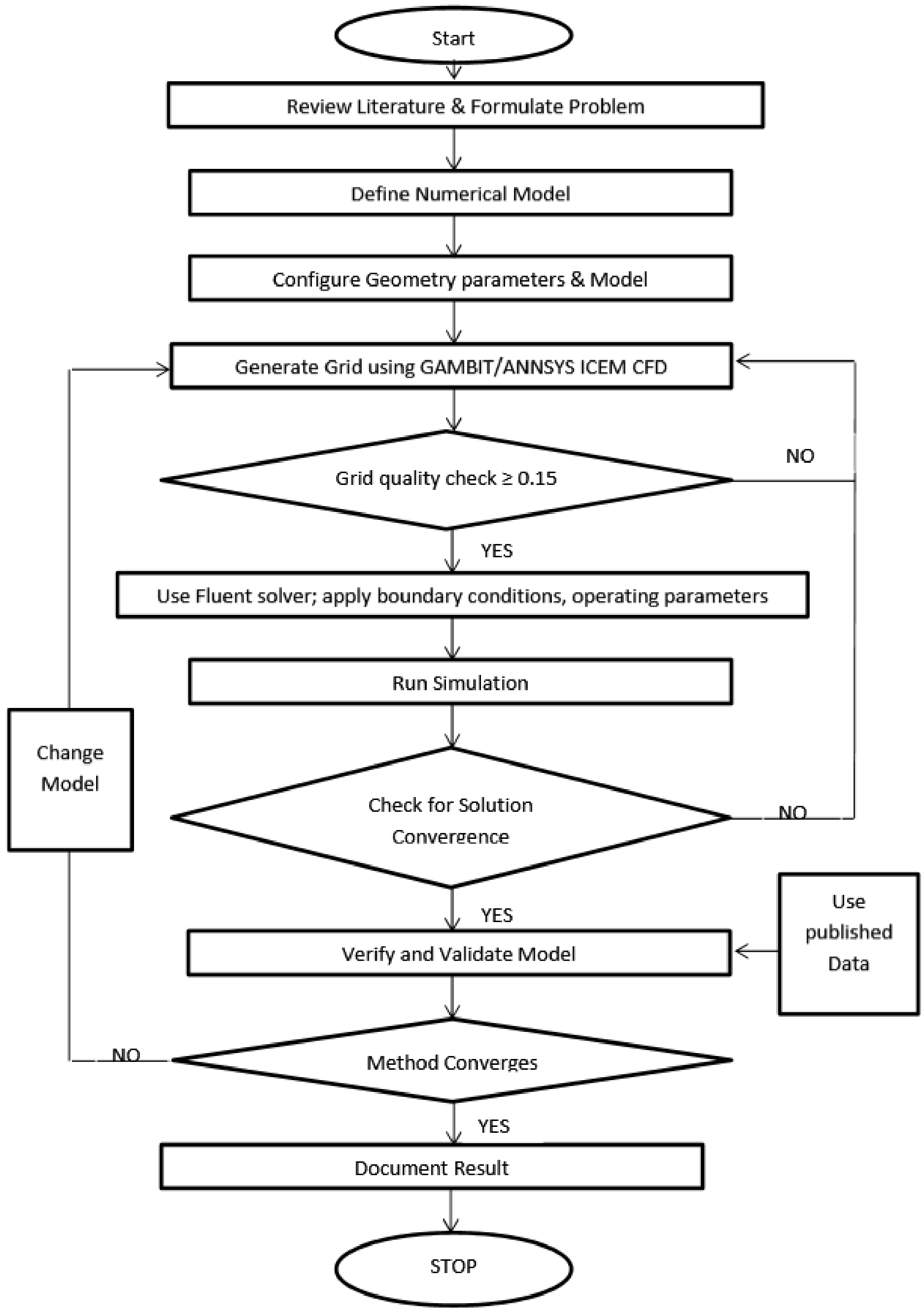


Figure10: Methodology adopted for Numerical Simulation

4.0 NOZZLE GEOMETRY DESIGN

The Supersonic separator uses a Convergent - Divergent nozzle. A Convergent Divergent nozzle or a De Laval Nozzle is a tube kind of thing where the area between the convergent and divergent section is pinched. These kinds of nozzles are used to accelerate the fluid flowing inside the nozzle to supersonic speeds.

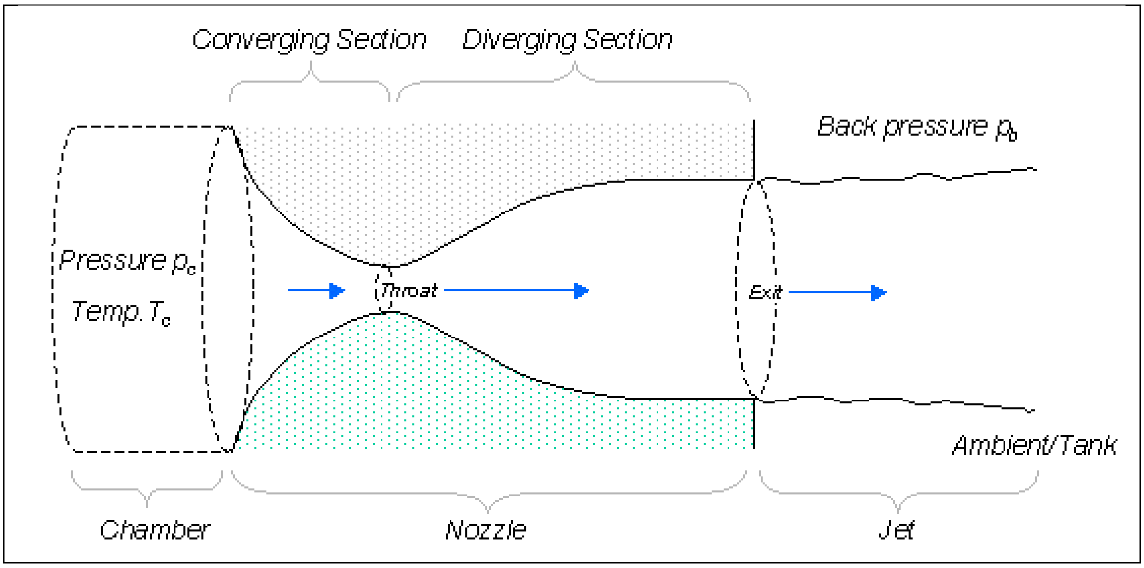


Figure 11: Convergent – Divergent Nozzle

The design of the Convergent - Divergent nozzle should be carefully done since minute disturbance in the nozzle section would create violent changes in the physical parameters of the fluid flowing. The Design of this Convergent Divergent nozzle is done using Matlab code and geometry is modelled in Gambit using the vertices generated by Matlab.

The steps involved in Modelling the Convergent - Divergent (De Laval) Nozzle are as follows:

1. Select nozzle equation

2. Program the equation in Matlab

3. Import the Vertices into Gambit

4. Model the nozzle in Gambit

5. Mesh the model

6. Specify Boundary Conditions

7. Export the Mesh

4.1 Nozzle Equation:

The Laval nozzle equation is taken from FOELSCH, K (1949), "The analytical design of an axially symmetric Laval nozzle for a parallel and uniform jet" [11]

The Equation used is as follows:

$$\frac{D - D_{cr}}{D_1 - D_{cr}} = 1 - \frac{1}{X_m^2}\left(\frac{x}{L}\right)^3 \qquad \left(\frac{x}{L} \le X_m\right)$$

$$\frac{D - D_{cr}}{D_1 - D_{cr}} = \frac{1}{\left(1 - X_m\right)^2}\left(1 - \frac{x}{L}\right)^3 \qquad \left(\frac{x}{L} > X_m\right) \quad \text{-------------------------------(1)}$$

Where:

D_1	=	Inlet Diameter
D_{cr}	=	Throat Diameter
L	=	Convergent Length
x	=	Distance between arbitrary cross section and the inlet
D	=	Convergent diameter at arbitrary cross section of x
X_m	=	0.3 – 0.7 times of x

The above cubic polynomial equation gives the contour of convergent section. This convergent part designed by the above equation will accelerate the flow of gas uniformly to the throat sections and helps to achieve the Mach as unity which is speed of sound.

4.2 Program the Equation in Matlab

The cubic polynomial equation is solved with the help of Matlab code. The code employed is shown in Appendix. The code employed uses simple "for loop" for discretization. The range for the loop is decided on the nozzle's convergent section length, inlet and outlet. Here, convergent section outlet will be starting point of throat area.

4.3 Import the Vertices into Gambit

A set of points or vertices generated using Matlab tool, these vertices are saved in notepad as a text file or a data (.dat) file. After opening Gambit theses vertices are imported as ICEM input. The following steps should be followed for importing the vertices.

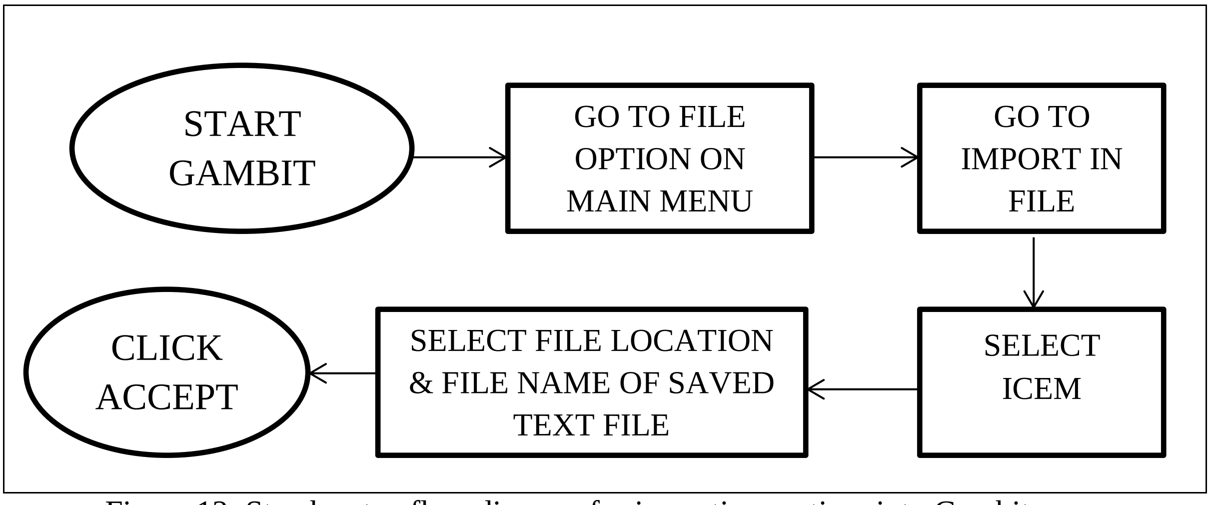


Figure 12: Step by step flow diagram for importing vertices into Gambit.

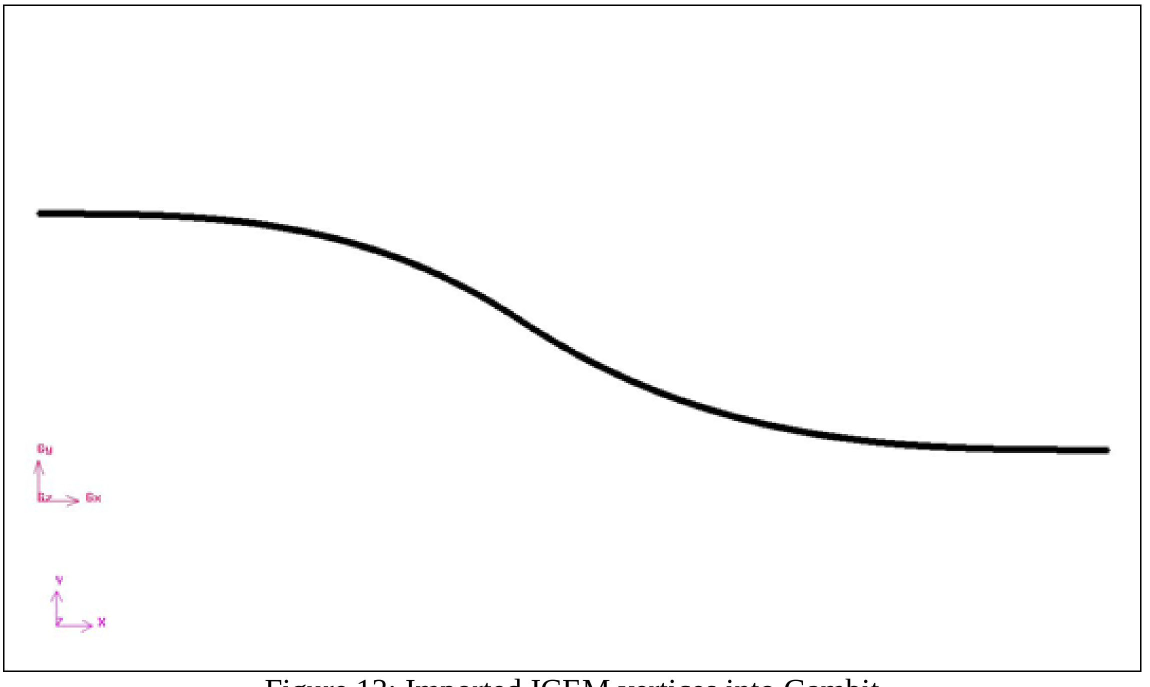


Figure 13: Imported ICEM vertices into Gambit

4.4 Model the Nozzle in Gambit

The nozzle modelling in Gambit is done by taking the reference of the following Schematic diagram.

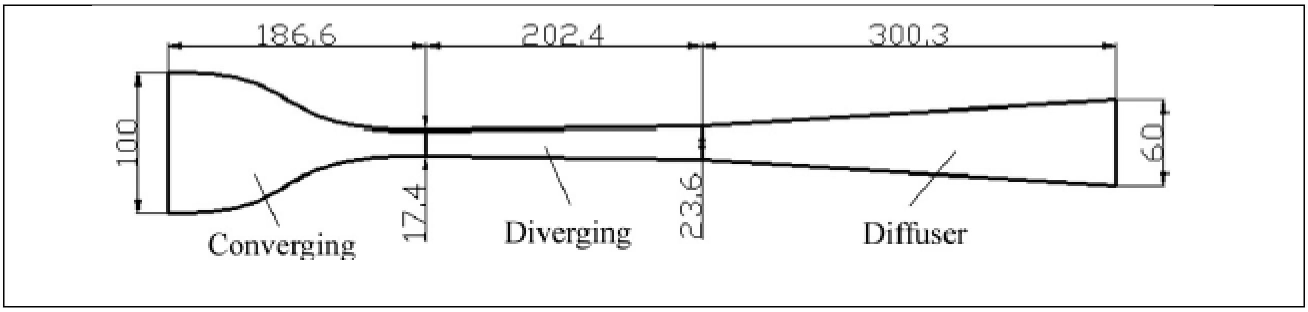


Figure 14: Schematic Diagram of a supersonic separator with geometry sizes.

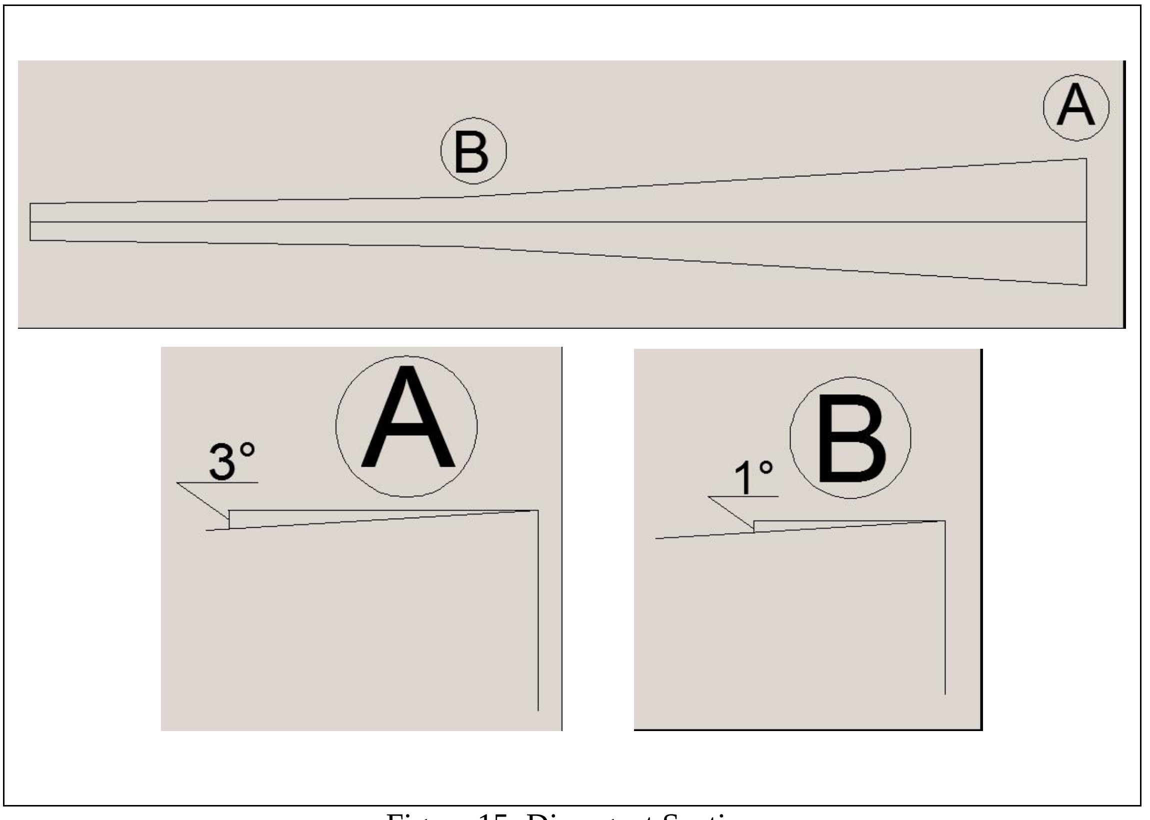


Figure 15: Divergent Section

Since the geometry is axisymmetric, one part of the geometry is sufficient for modelling and meshing. This is because the solver has the option of considering the geometry as axisymmetric.

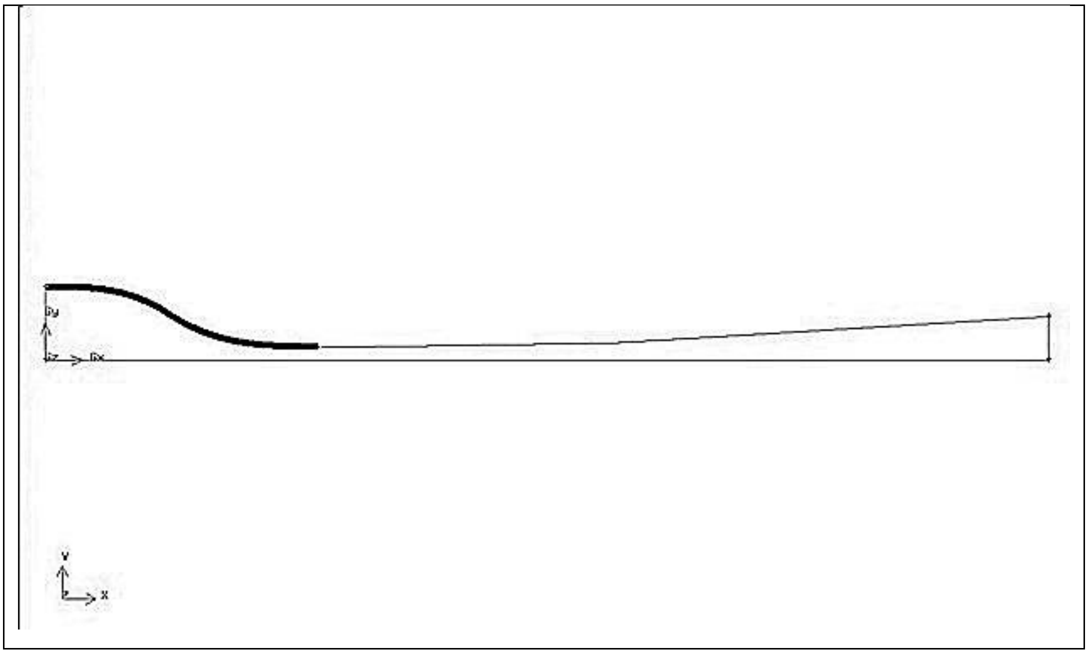


Figure 16: Nozzle Geometry Modelled in Gambit

4.5 Mesh the Model

Meshing the model plays a vital role of all the activities since mesh quality defines the accuracy of the result. Since the model is complete 2 dimensional (2D), only Quad type cells are applied. Unstructured mesh is employed due to the irregularities of the nozzle profile. .

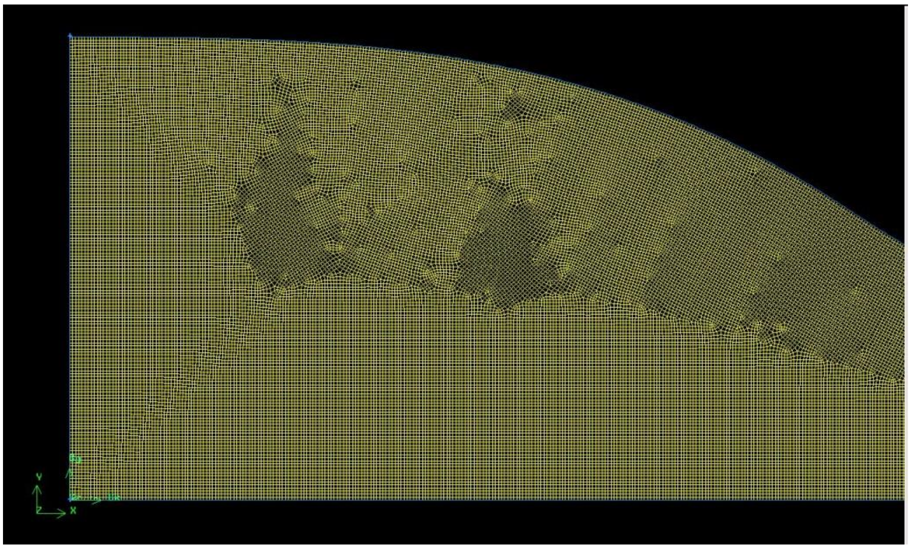


Figure 17: Convergent section Quad Mesh

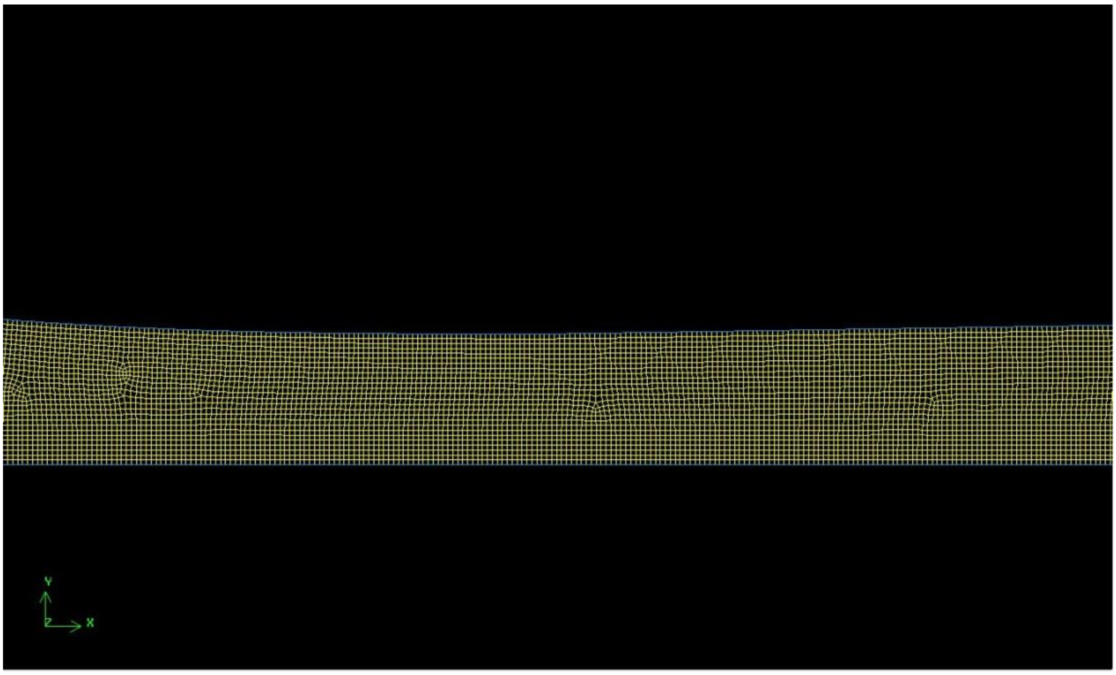


Figure 18: Throat section Quad Mesh

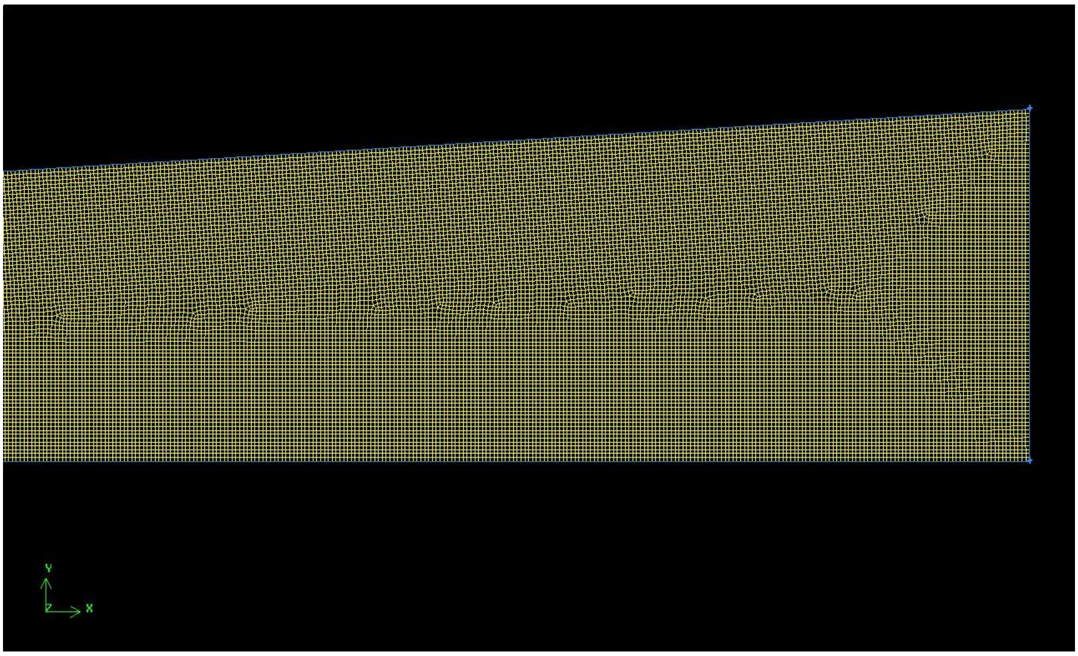


Figure 19: Diffuser section Quad Mesh

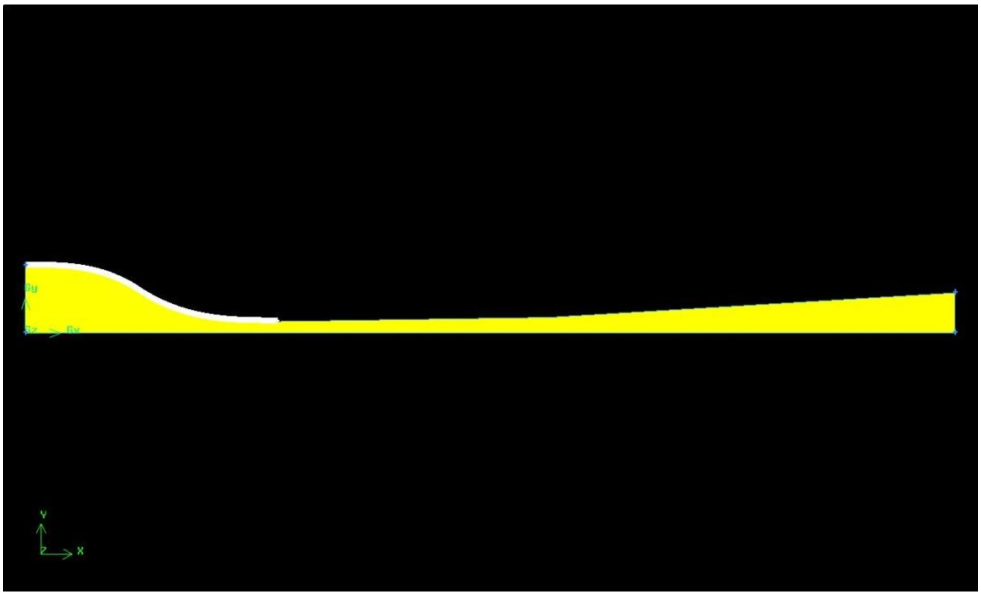


Figure 20: Mesh Generated in gambit

4.6 Specify Boundary Conditions

Boundary conditions are to be specified for the model. Accordingly it will be define in the solver when exported. These boundary conditions specification plays a crucial role while working with solver, so carefully consider the boundary conditions. The nozzle entrance is taken as Pressure Inlet, and the Diffuser exit is taken as Pressure Outlet. Since the problem is axisymmetric, the axis line is taken as Axis. The nozzle profile is considers as wall.

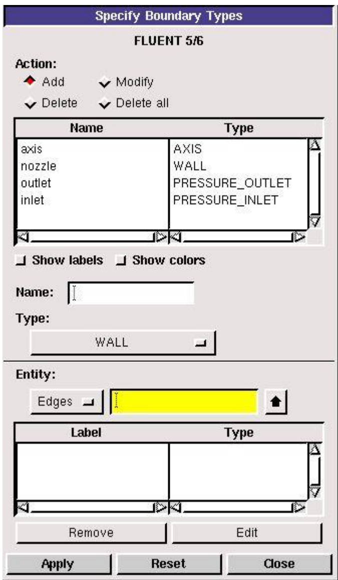


Figure 21: Specifying boundary conditions

4.7 Export the Mesh

The Mesh Generated should be exported in order to use by any solver. The simple steps involved in exporting the mesh file are as follows.

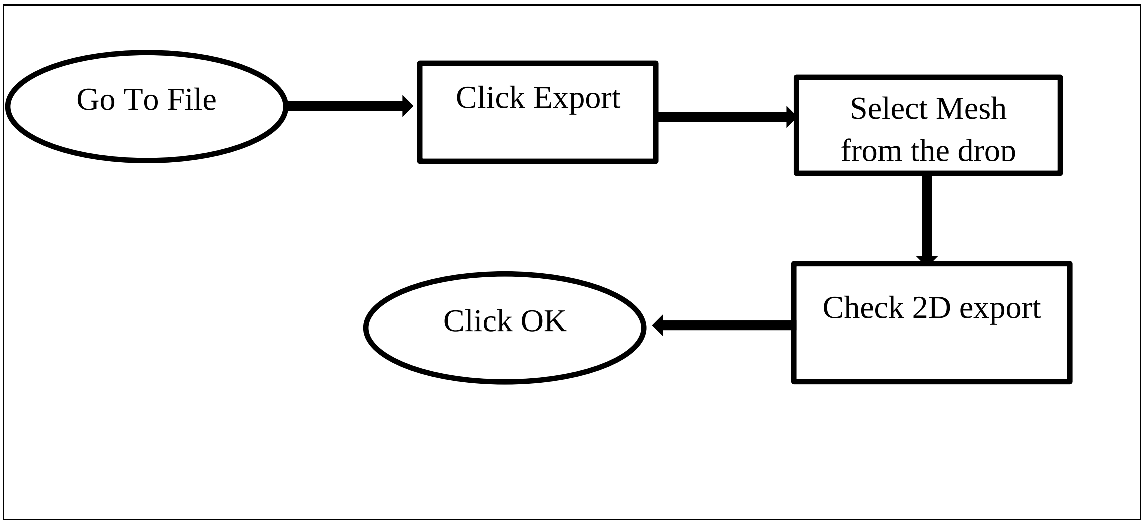


Figure 22: Flow Diagram to export Mesh

The exported mesh file can be used by any supported solvers. The process of modelling in gambit is a bit tedious compared to other Cad modelling tools. But the mesh generated in gambit will give high level quality mesh.

The Equisize Skewness can be verified in gambit by checking the worst element size. For the nozzle modelled, the worst cell size ratio is of 0.412124. This ratio should not be more than 0.6. Hence the mesh generated is of good quality.

5.0 CFD SOLVER

The CFD Solver employed to solve the problem is Ansys Fluent 14.0. Before starting the problem, the boundary conditions of the model have to be defined in the Gambit. There is a provision of changing in Fluent also, but for time saving and accuracy the boundary conditions have to be changed in Gambit. If any other Cad package is being used, the boundary condition provision may not be available, then it should be done in Fluent only.

5.1 Problem Setup

Step 1: General Options

Mesh

- The problem set up is the initial activity done after reading the mesh file which is created in Gambit. Check the mesh quality. The detail of the mesh quality for this problem is shown in Appendix.
- Scale the geometry in the General option. Change the units to desire. In this case it is all ‘mm’.

Solver

- The Density based solver is employed, since the problem is using compressible fluids.
- The velocity formulation will be Absolute.
- Steady State simulations are considered.
- The model is axis symmetry

6.0 RESULTS AND DISCUSSION

6.1 Model Validation

The Geometry we considered is verified with the work of Arina[]. Arina's work is done with air as a fluid. So, we tested our model also with air as fluid. The obtained results are in quite acceptable range.

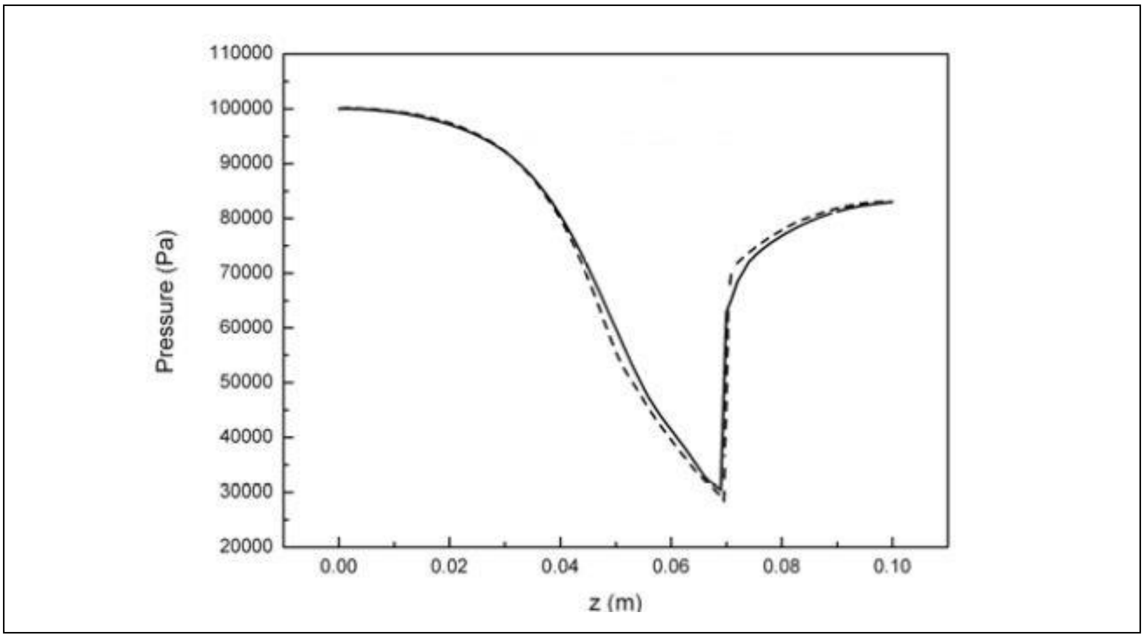


Figure: Arina's Model Results

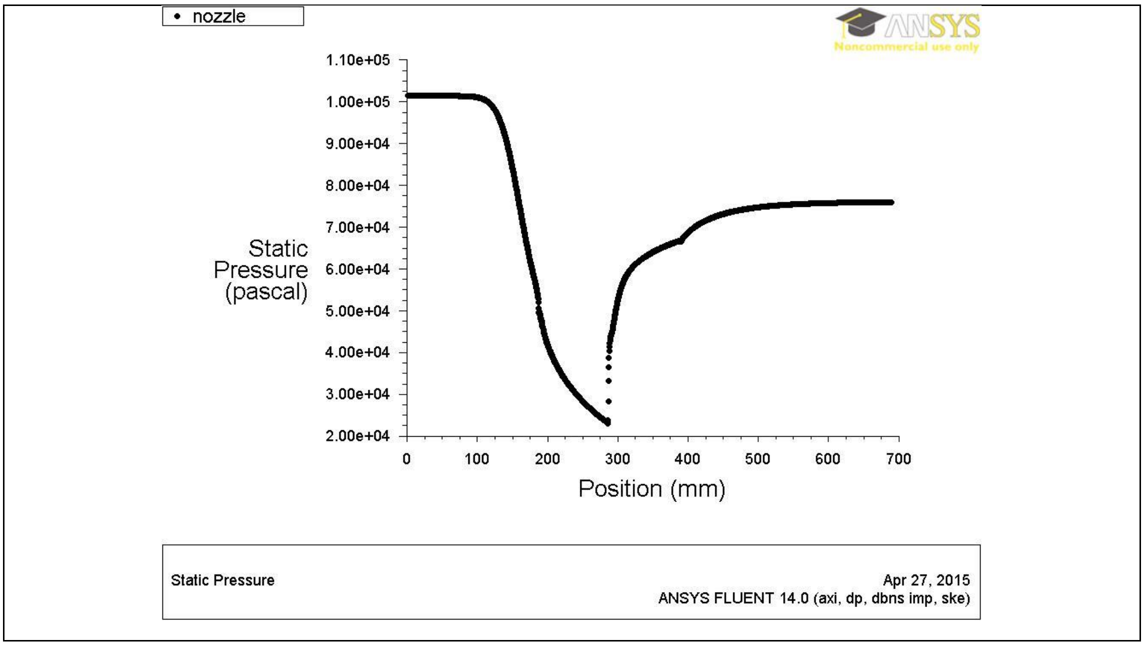


Figure Model validation with Arina's

6.2 Grid Independency

Grid Independency tests are conducted the geometry with different sizes of the grids. Same Operating conditions are employed to different sizes of grids, where the numbers of cells differ from grid to grid. The numbers of cells are ascended gradually. One parameter is taken constant for verification for all the grid sizes. In this case the maximum Mach number is taken as constant parameter and is compared with all the grid sizes. The operating parameters consider for the test are shown in the table

Table: Operating Conditions for Grid Independency tests

Fluid	Air
Density Equation	Redlich Kwong Real Gas Equation
Inlet Pressure	101325 Pascal's
Inlet Temperature	300 K
Outlet Pressure	70927.5
Outlet Temperature	280 K
Operating Pressure	0
Number of Iterations	100000

The sizes of the grids and the Mach numbers achieved are shown in the following table

Table: Grid Independency test results

CASE	SIZE	MAX MACH
1	13395	1.699
2	55033	1.723
3	124508	1.724

Here in the case of 2 & 3 the maximum Mach number achieved is almost equal. The percentage variation is less than 10 %, which is quite acceptable. The test can be carried out with case 2 size mesh but for accuracy and for exact location of the shock in the supersonic separator the test is conducted with case 3 size.

6.3 Simulation Results for Air

The initial simulation is run with air as fluid. The obtained results are as follows.

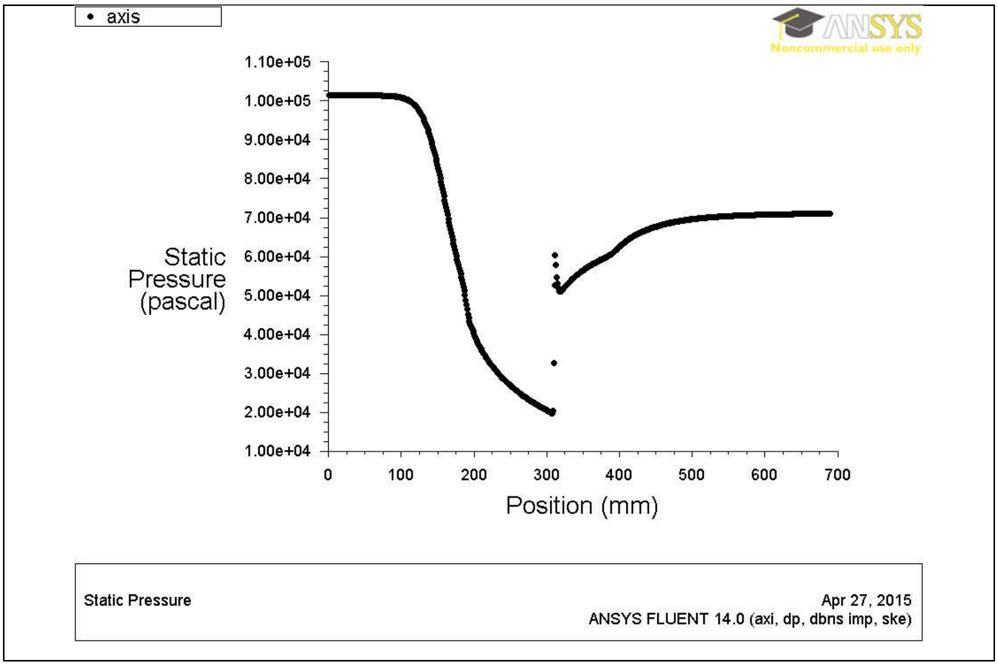


Figure : Pressure Plot for Air Simulation

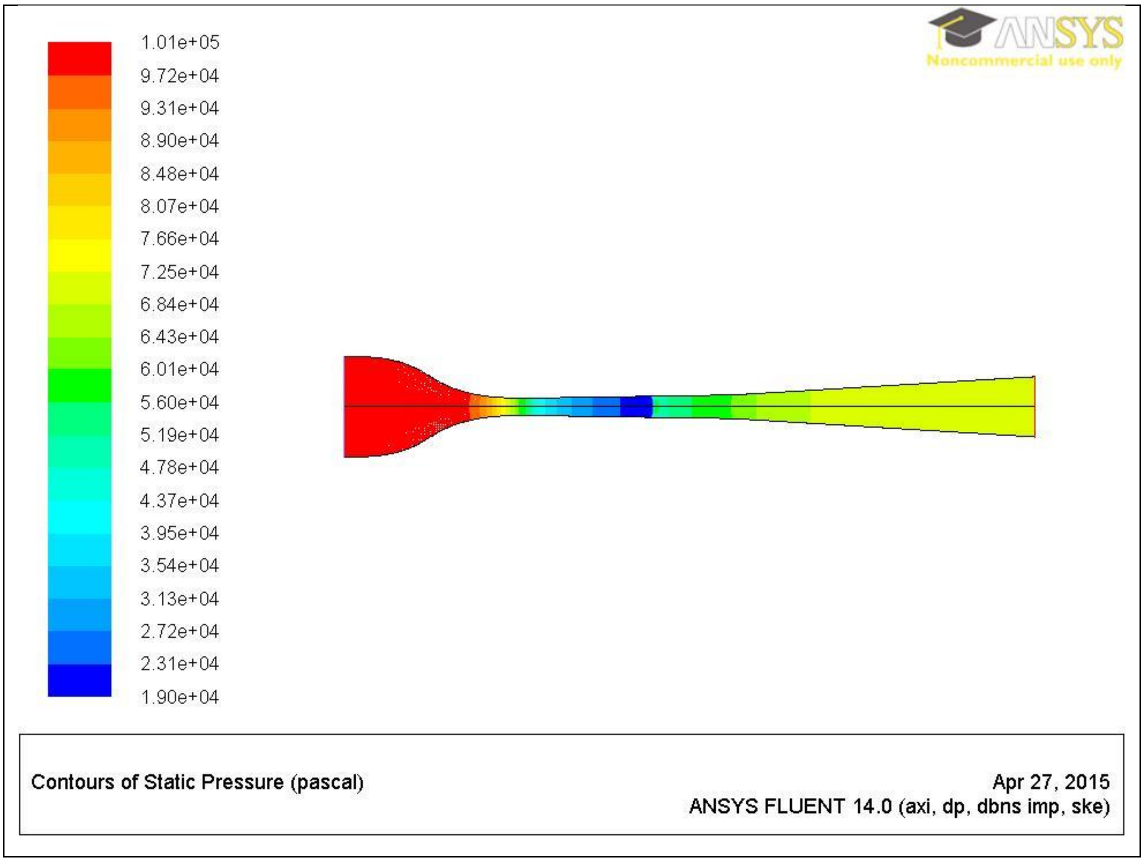


Figure Pressure Contour for Air Simulation

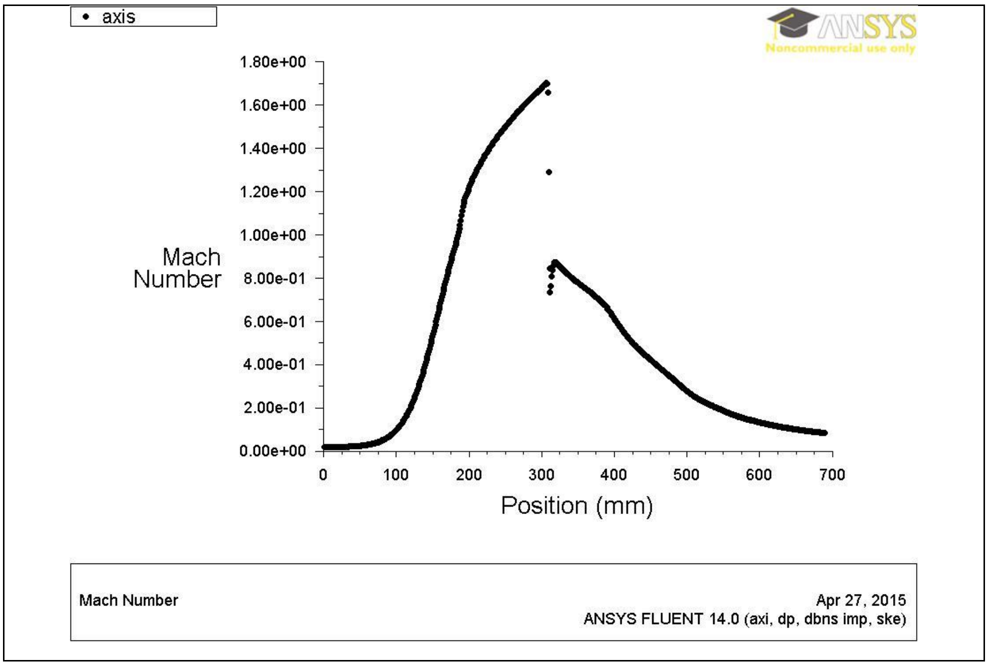


Figure: Mach Plot for Air Simulation

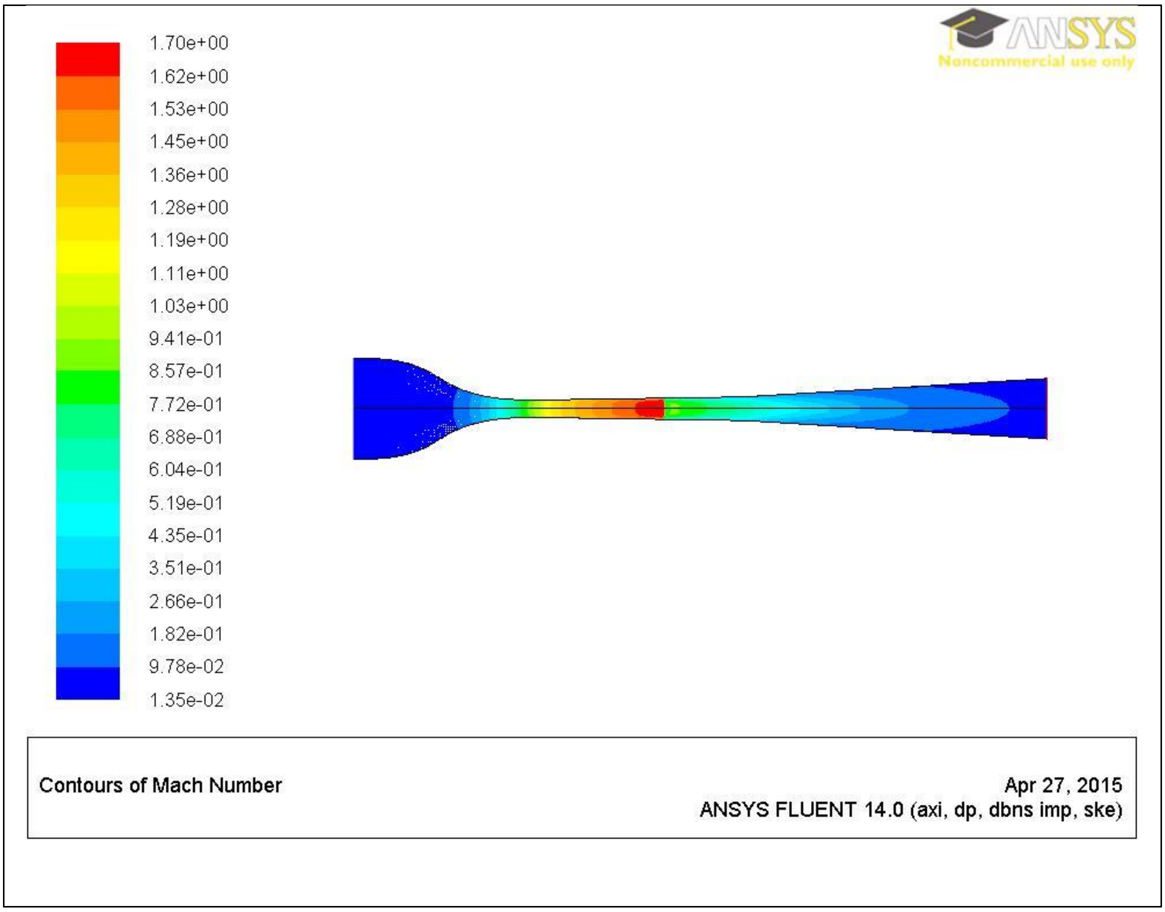


Figure: Mach Contour for Air Simulation

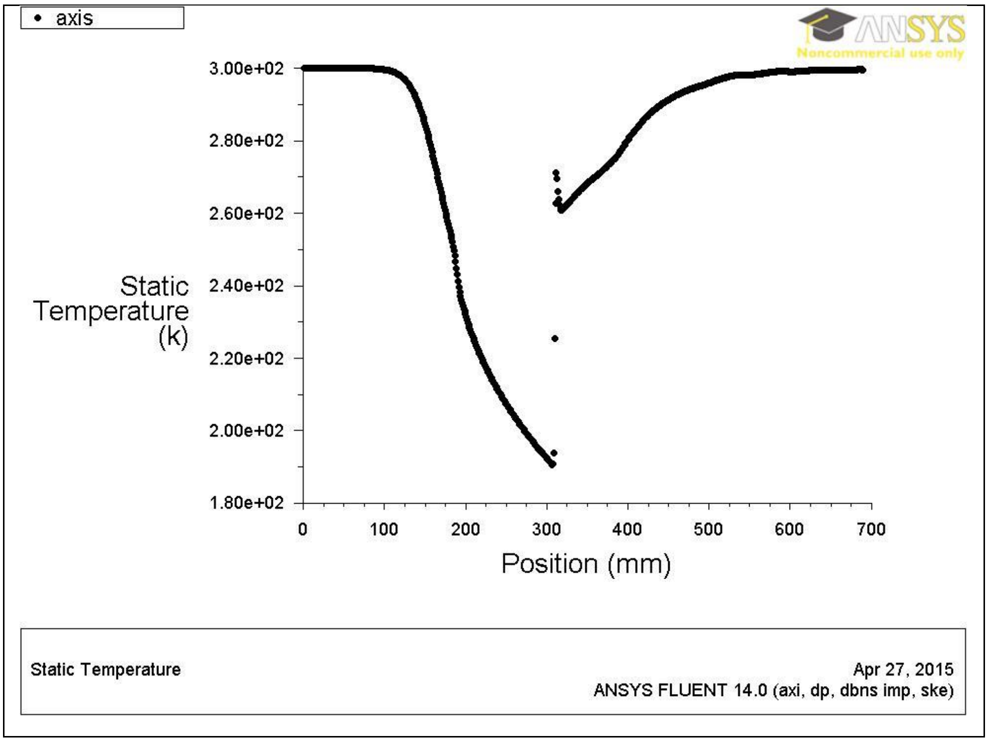


Figure: Temperature plot for Air simulation

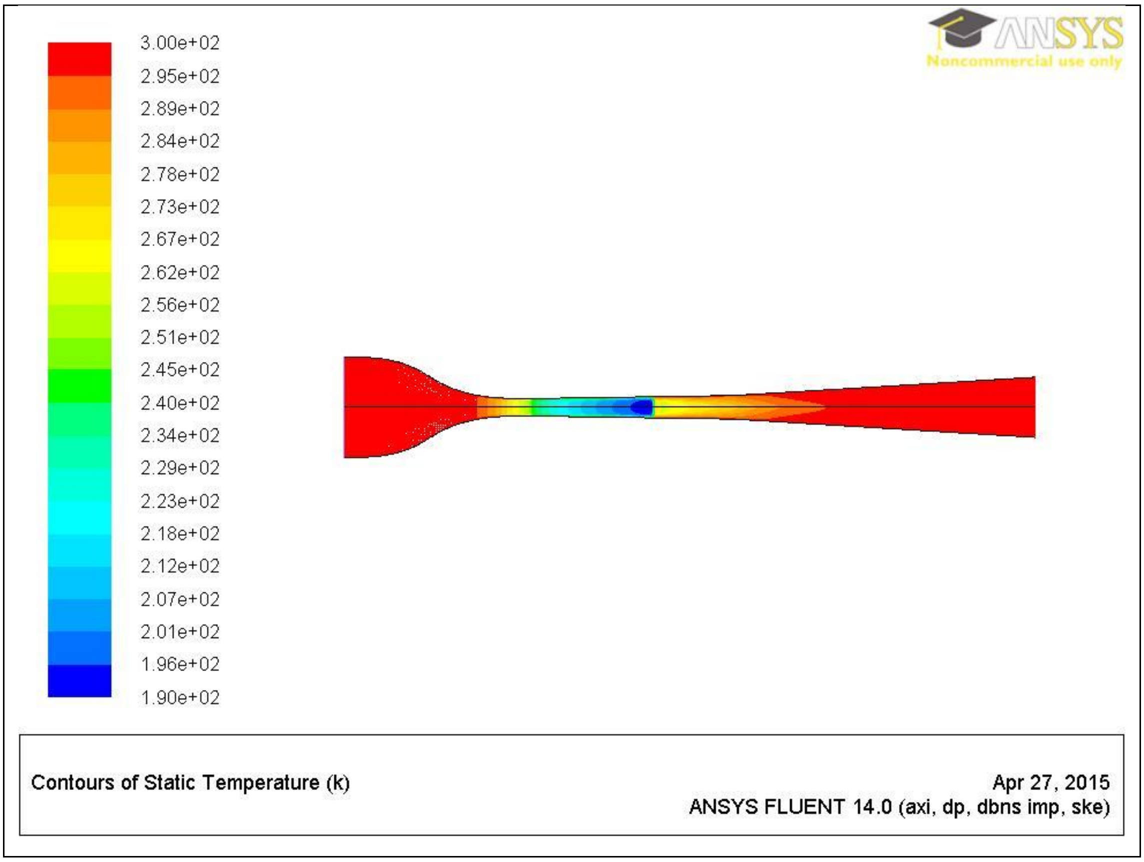


Figure: Temperature Contour for Air Simulation

6.4 Simulation Results for Methane

The second simulation is run with Methane as fluid. The obtained results are as follows.

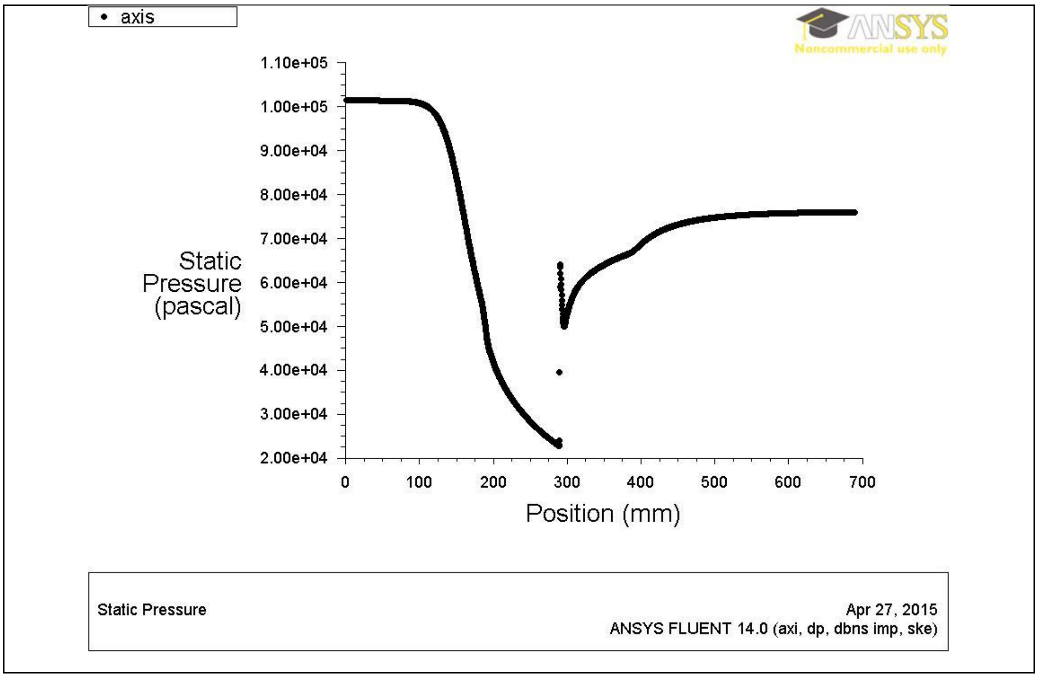


Figure : Pressure Plot for Methane Simulation

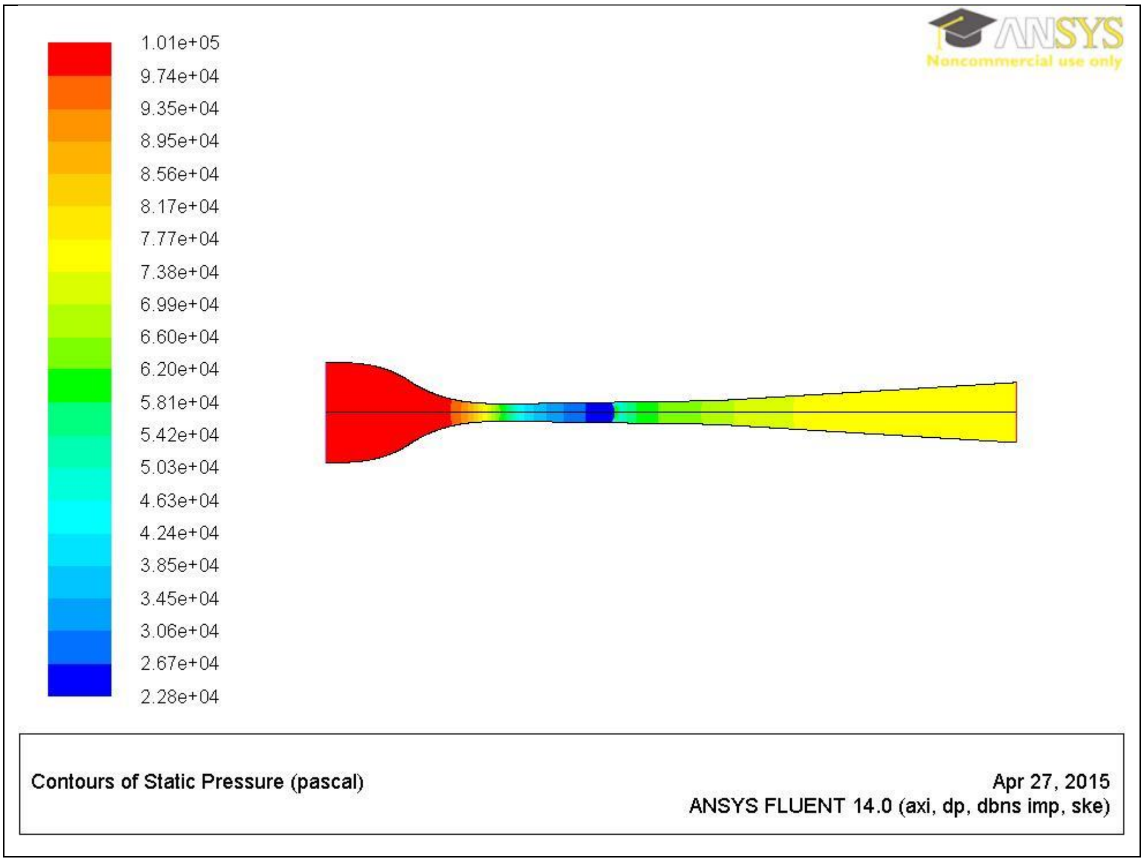


Figure: Pressure Contour for Methane Simulation

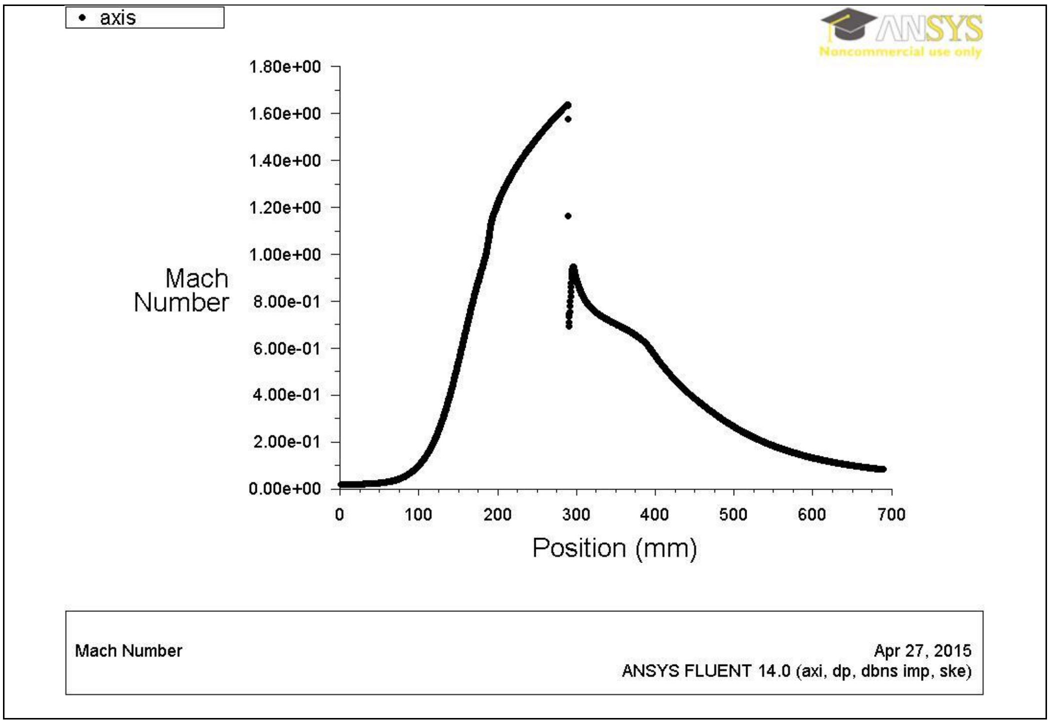


Figure : Mach Plot for Methane Simulation

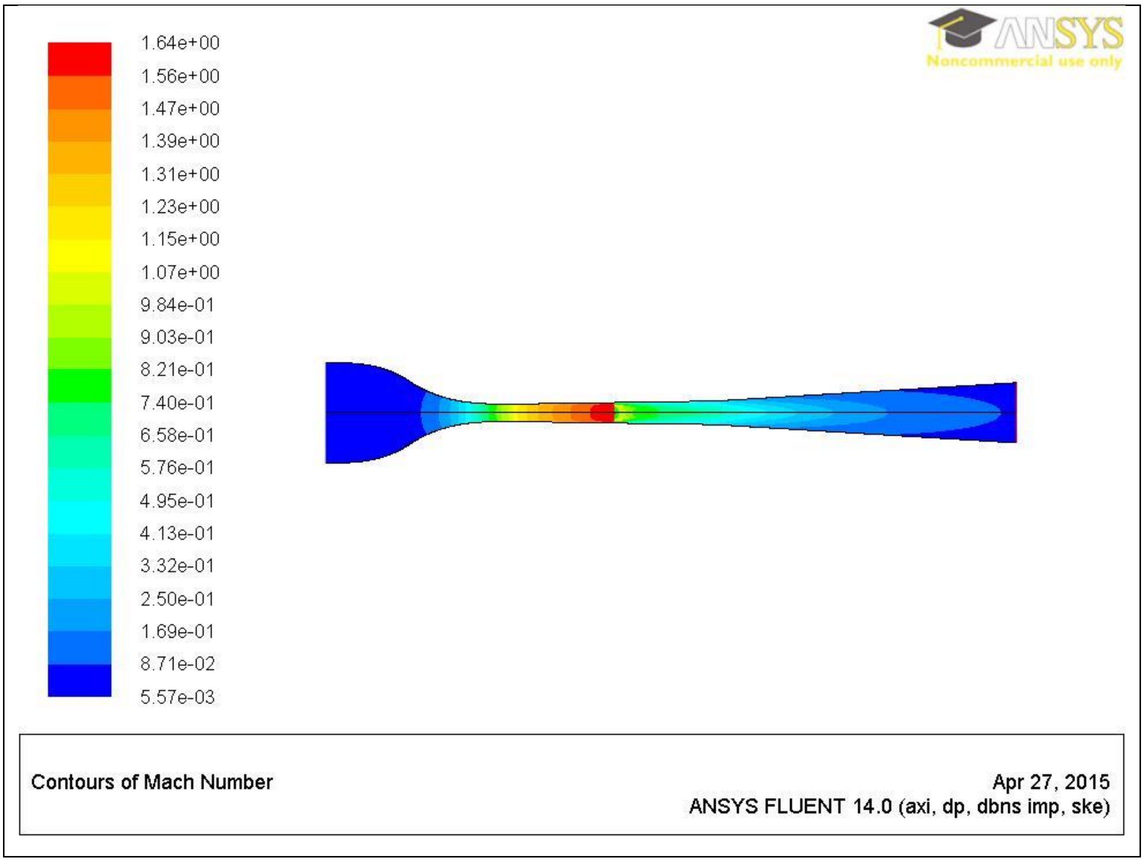


Figure: Mach Contour for Methane Simulation

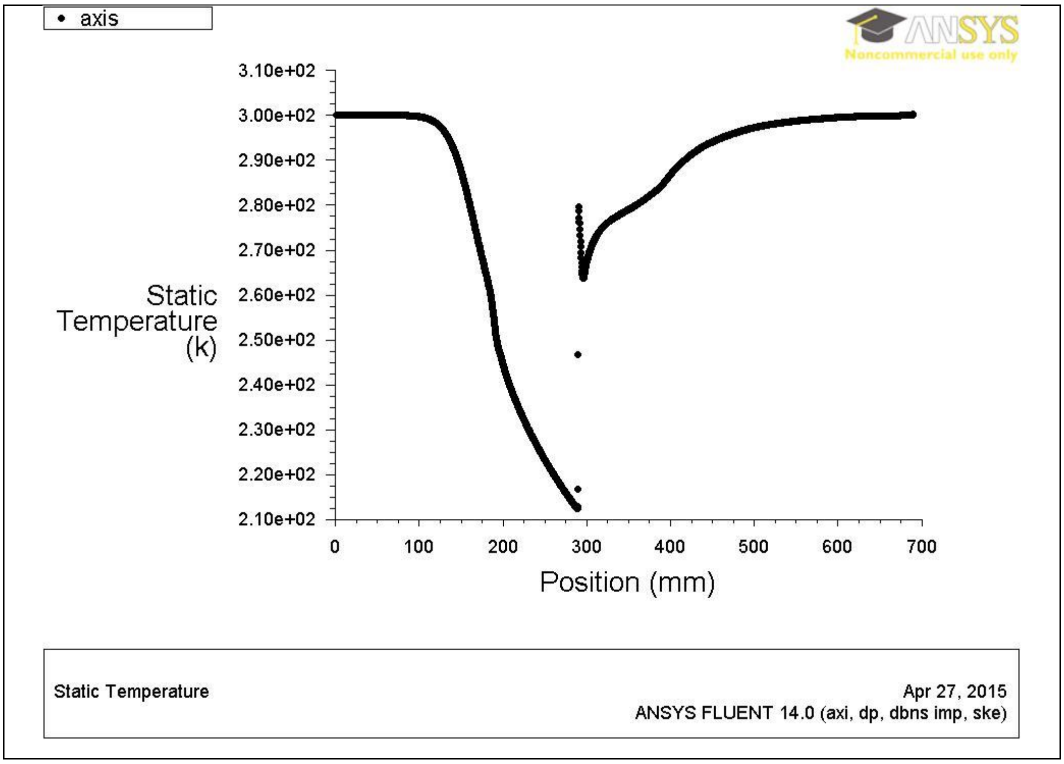


Figure: Temperature Plot for Methane Simulation

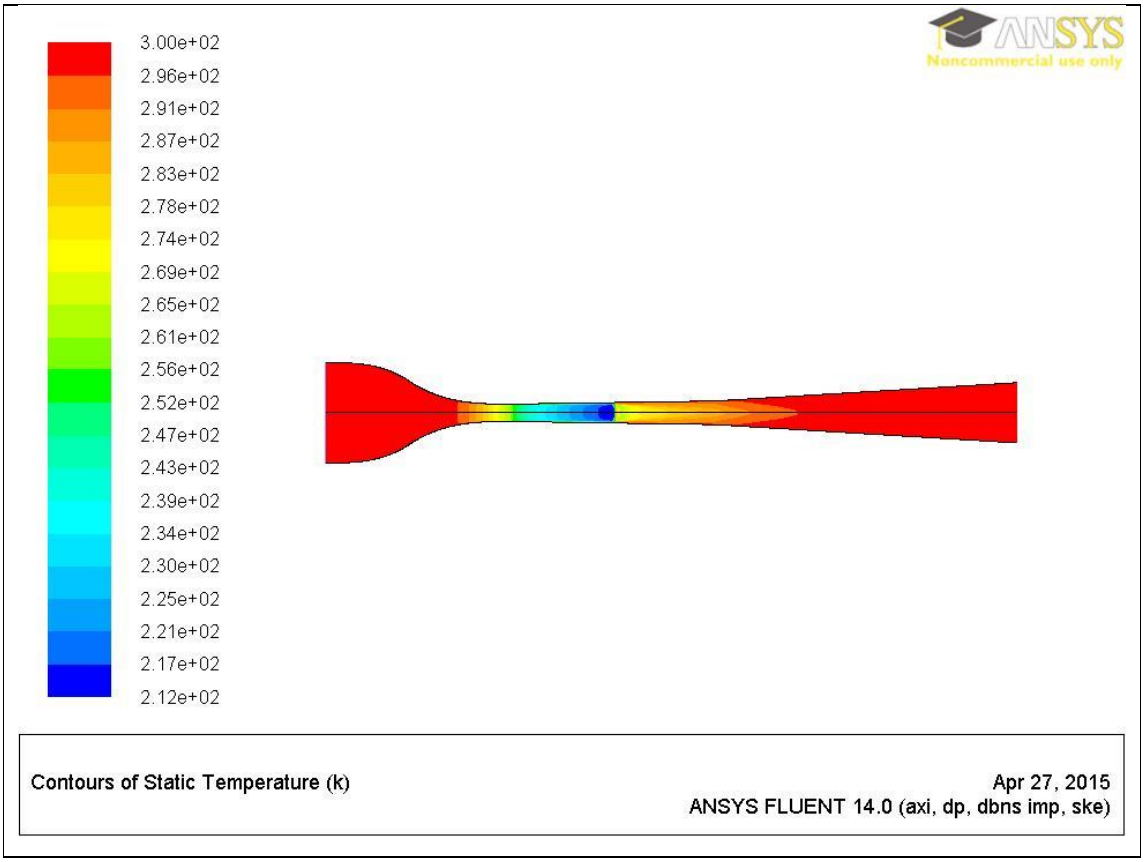


Figure: Temperature Contour for Methane Simulation

6.5 Simulation Results for Natural Gas

The Third simulation is run with Natural Gas as fluid. The obtained results are as follows.

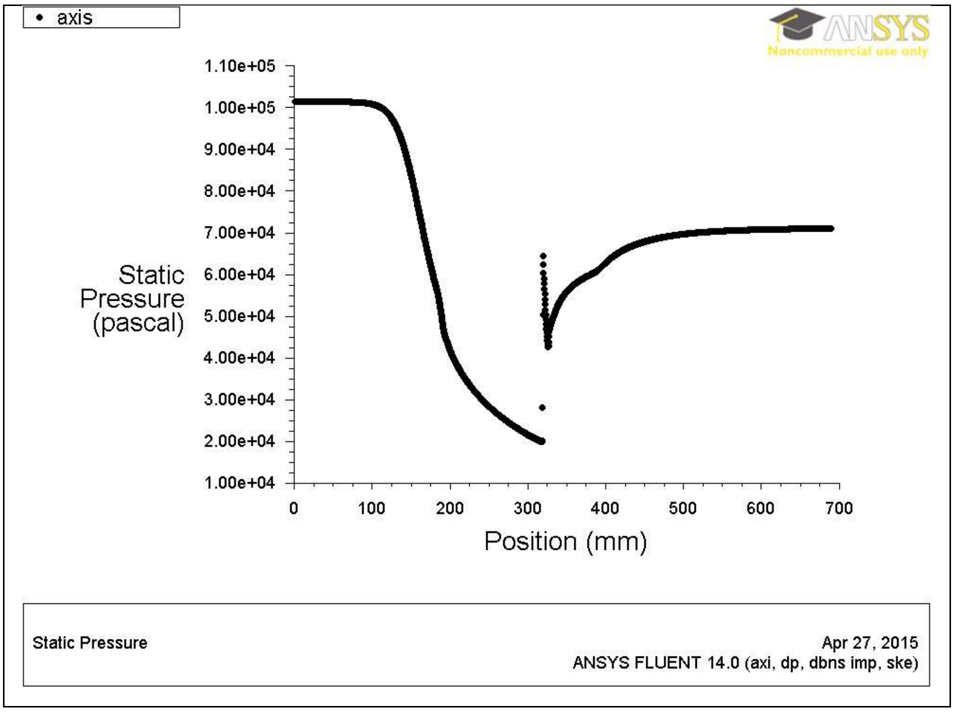


Figure: Pressure Plot for Natural Gas Simulation

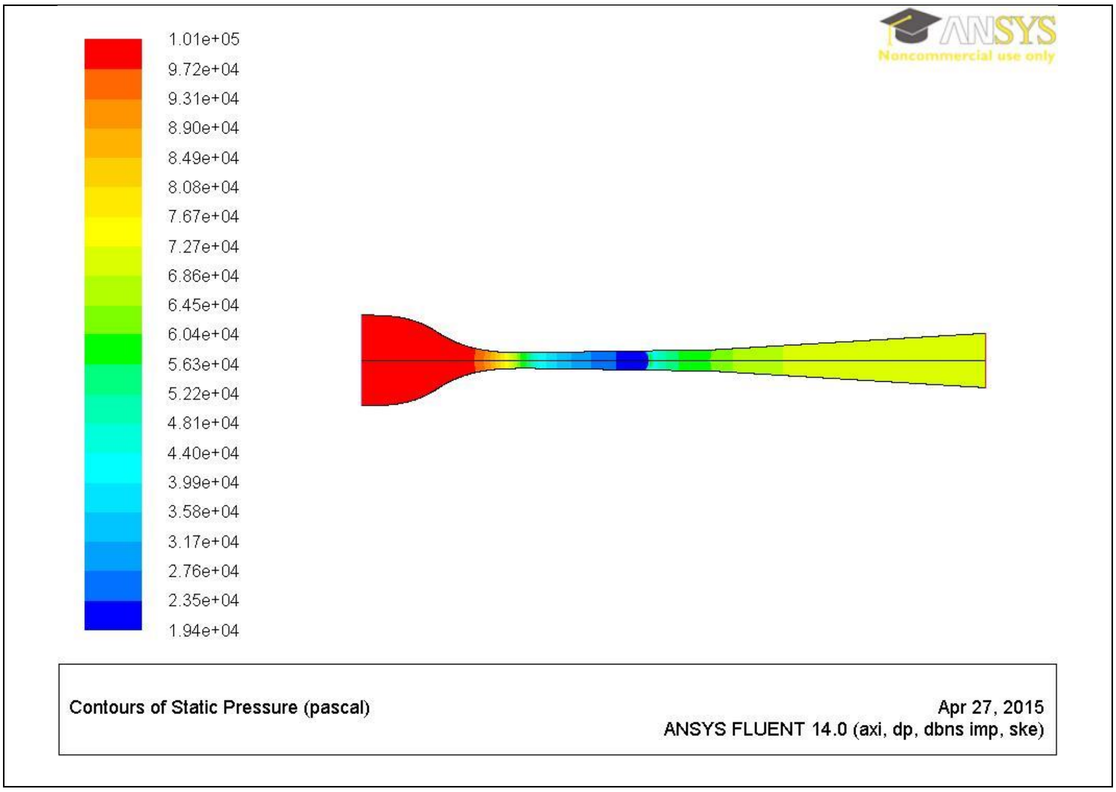


Figure: Pressure Contour for Natural Gas Simulation

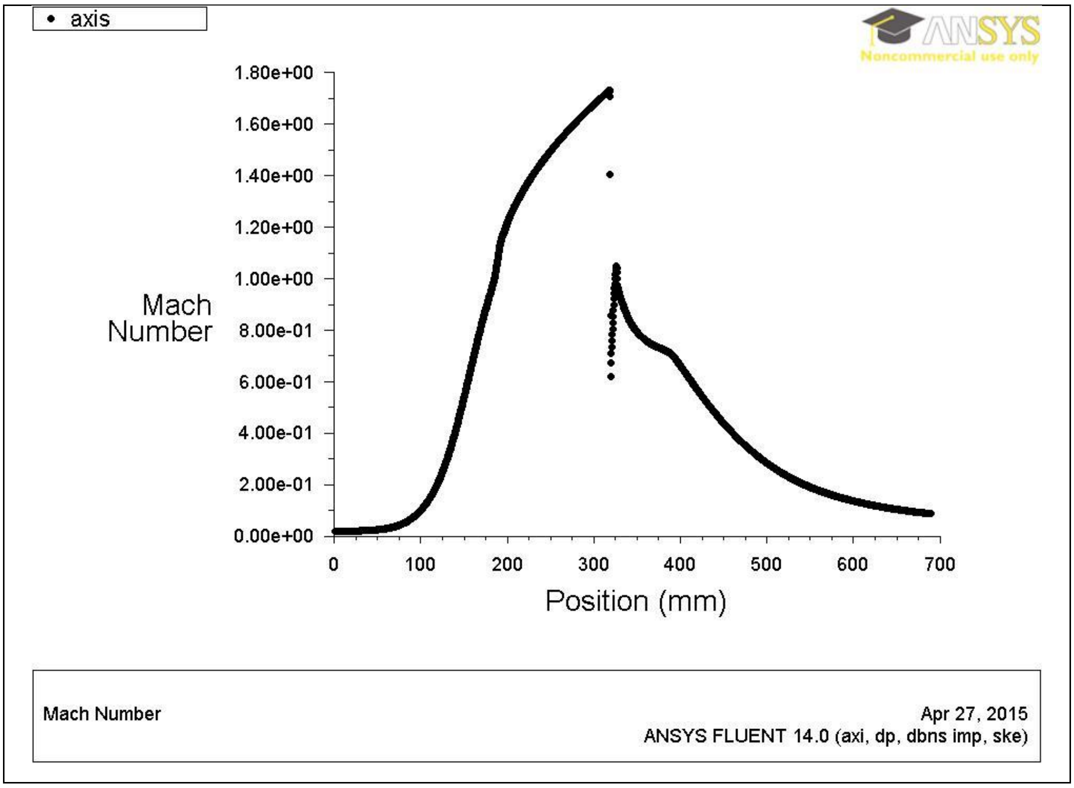


Figure: Mach Plot for Natural Gas Simulation

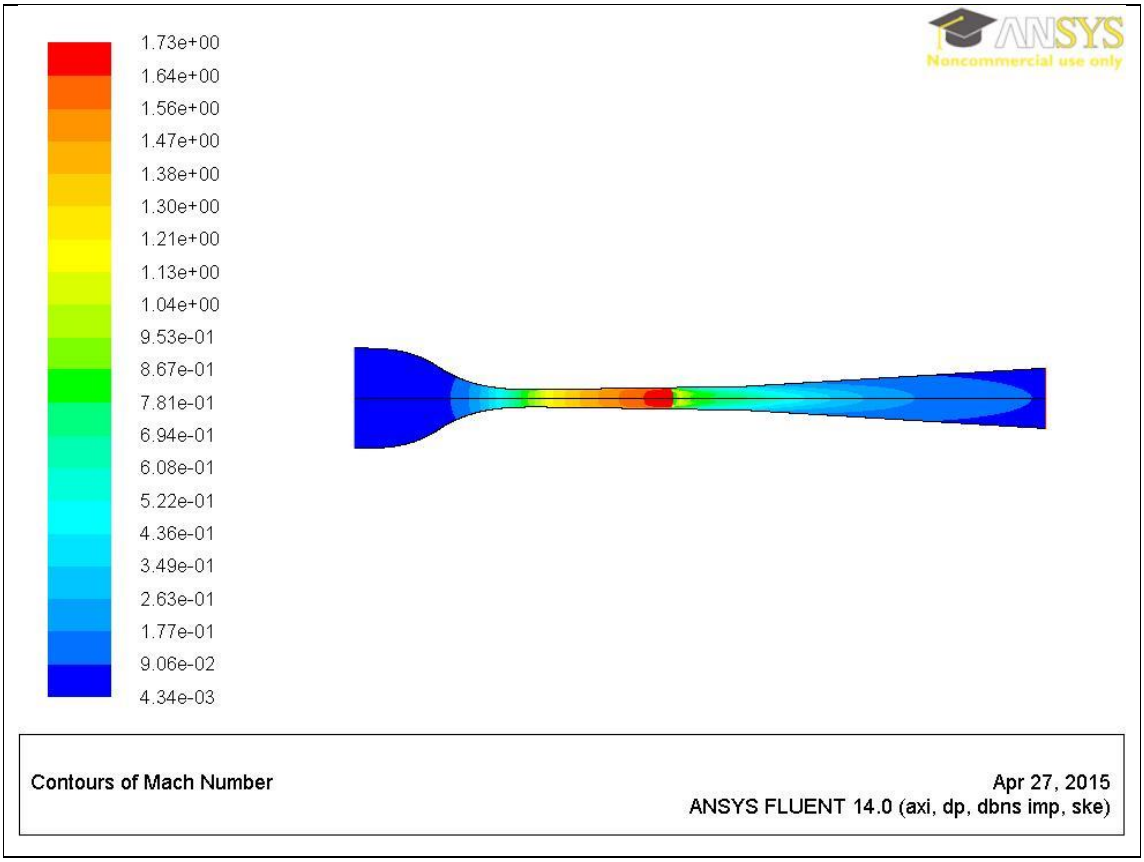


Figure: Mach Contour for Natural Gas Simulation

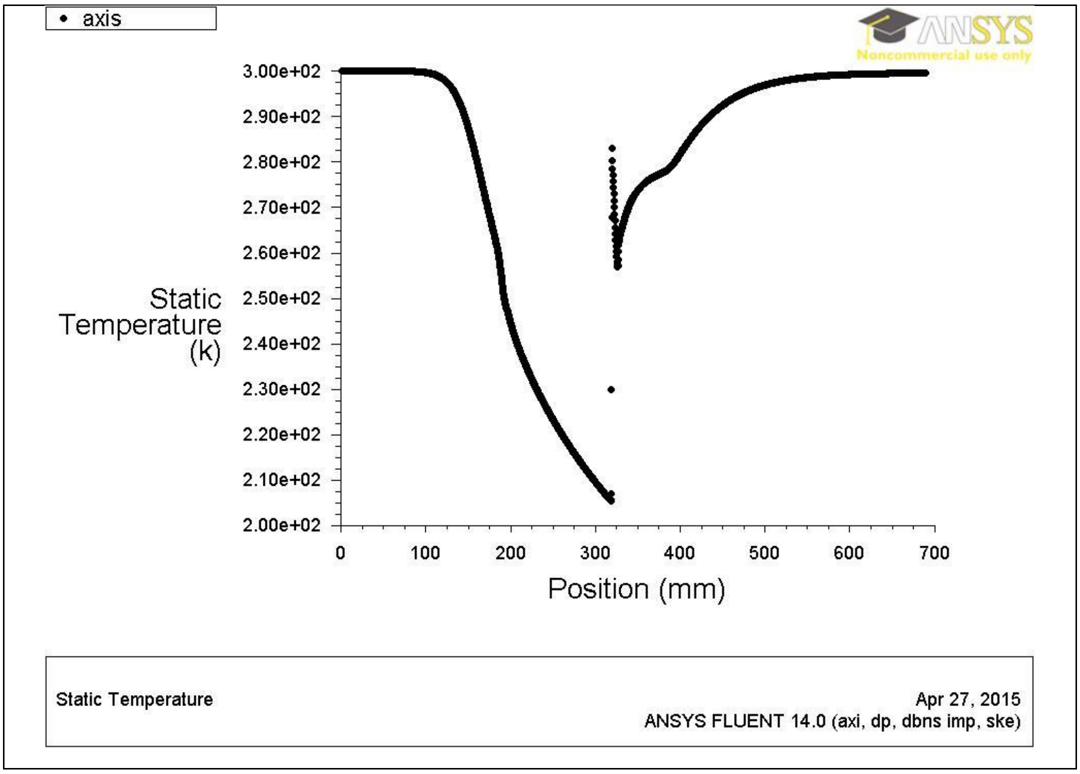


Figure: Temperature Plot for Natural Gas Simulation

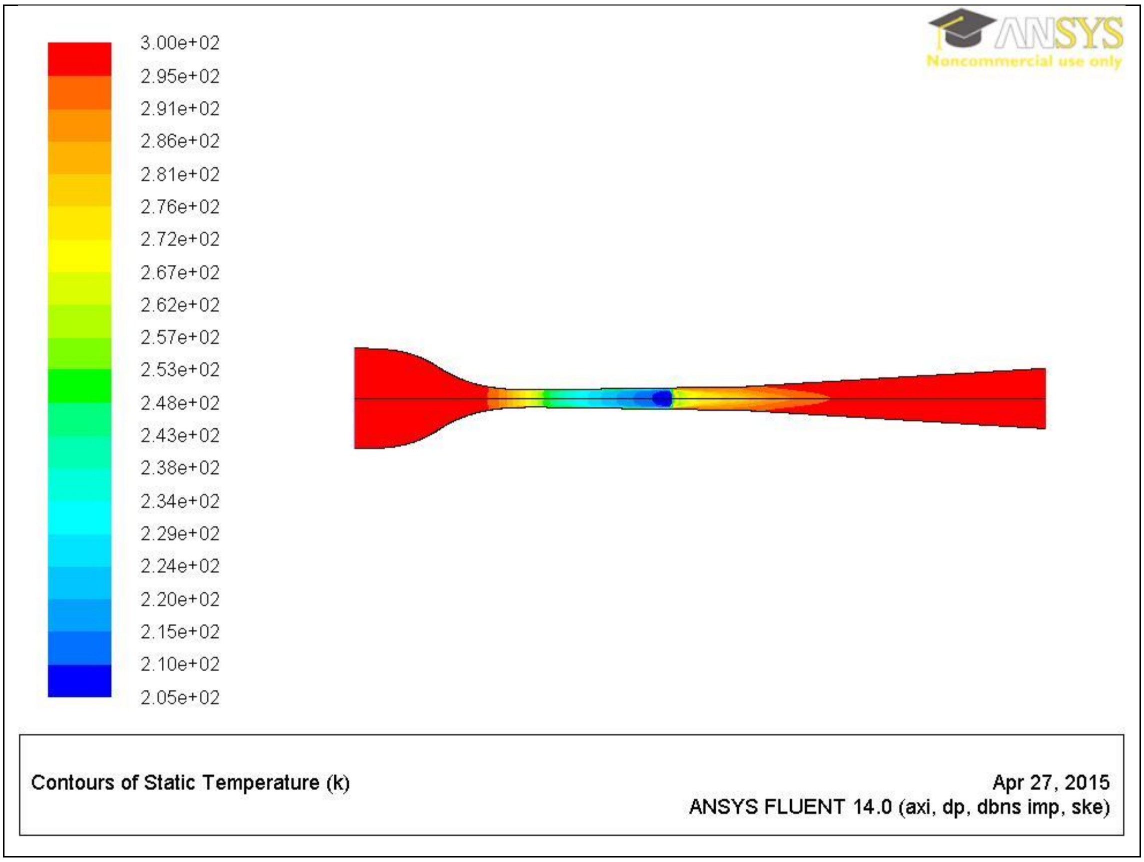


Figure: Temperature Contour for Natural Gas Simulation

6.6 Comparative Study of all the Fluids

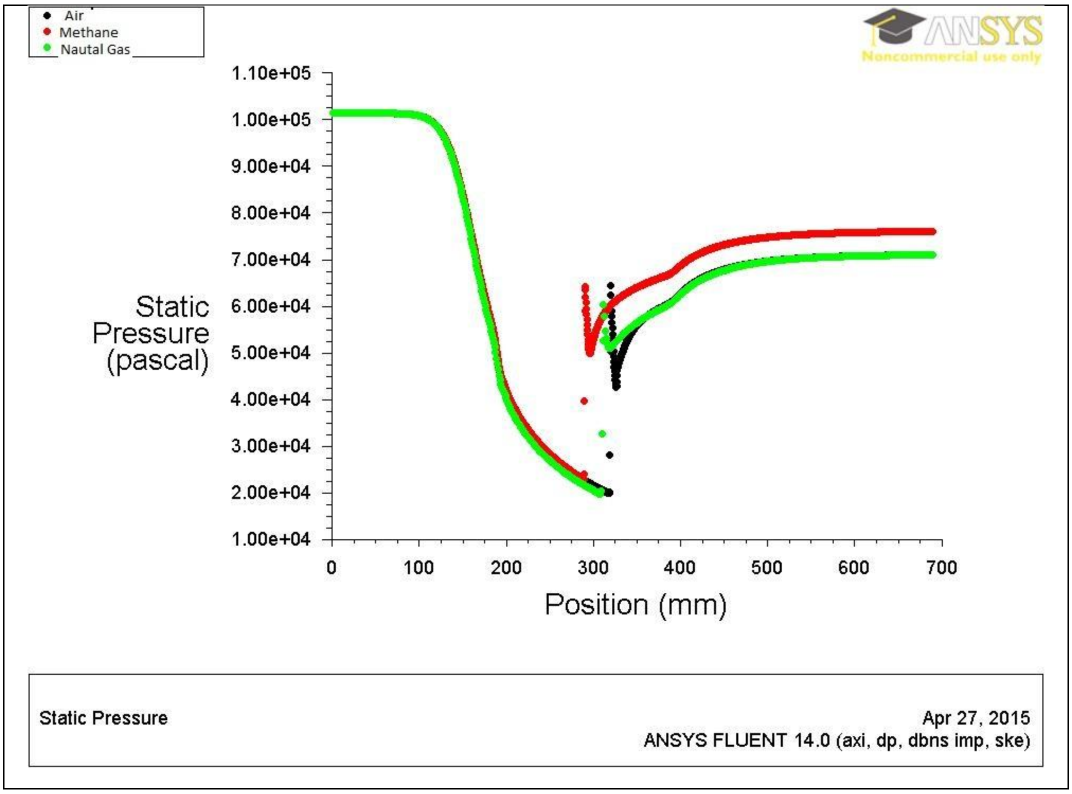


Figure: Pressure Plots Comparison for all the Simulations

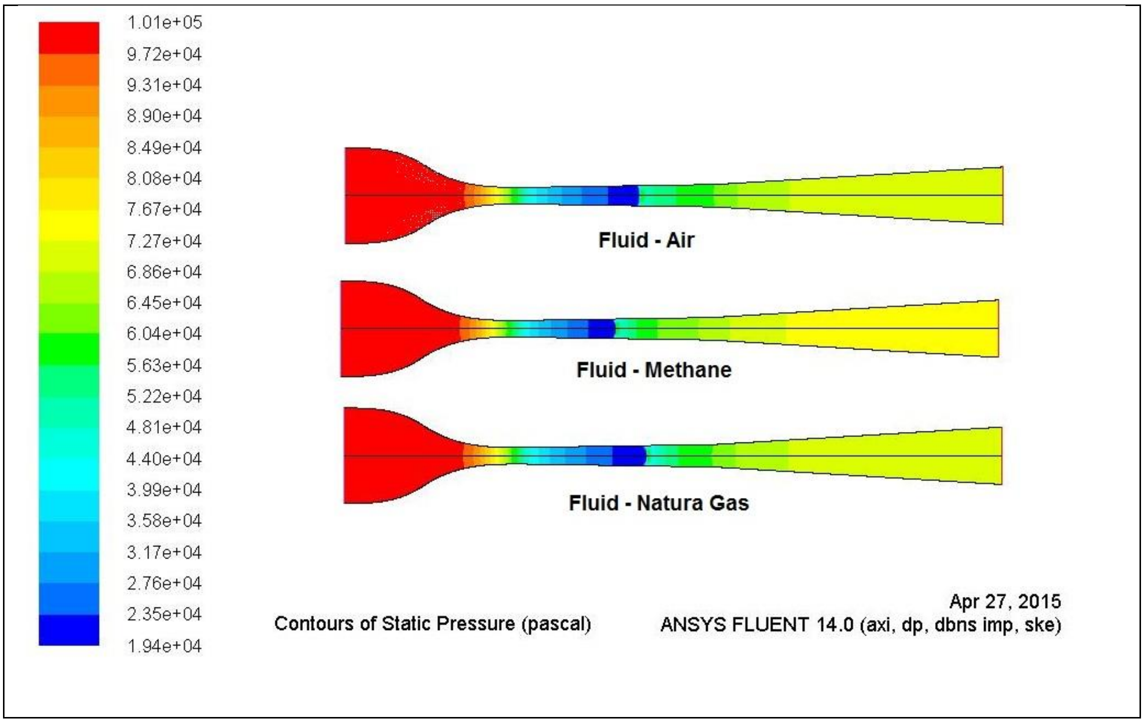


Figure: Pressure Contours Comparison for all the Simulations

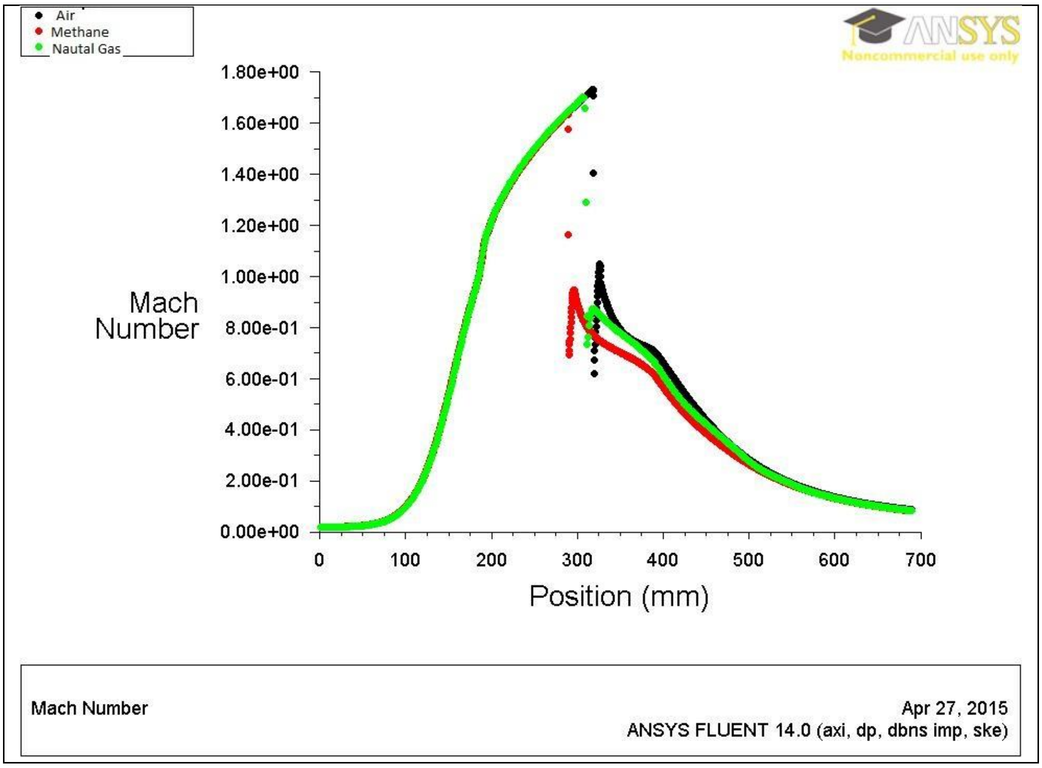


Figure: Mach Plot Comparision for all the Simulations

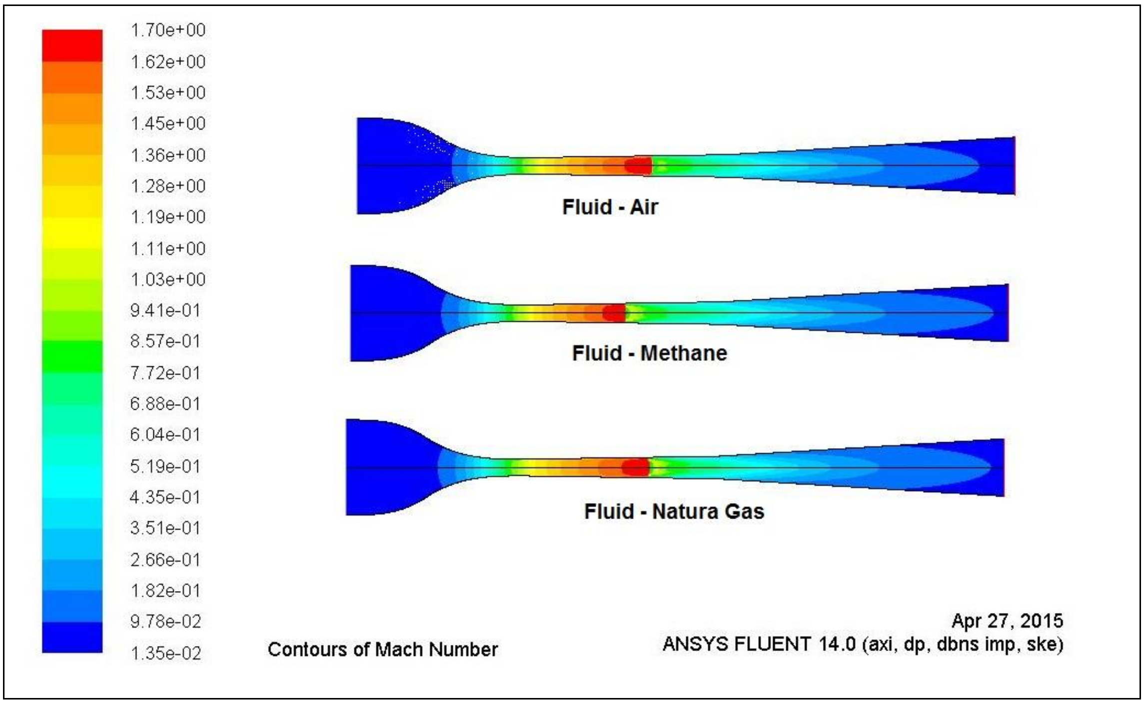


Figure: Mach Contour Comparision for all the Simulations

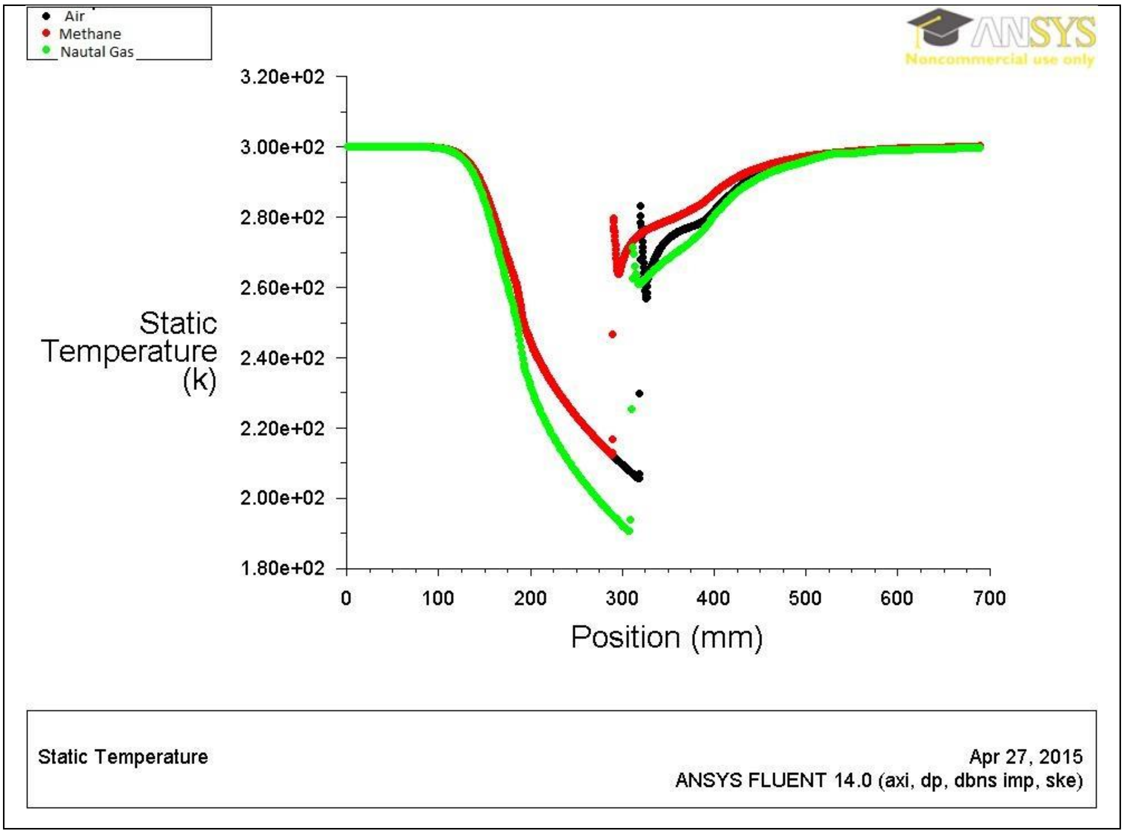


Figure: Temperature Plot Comparision for all the Simulations

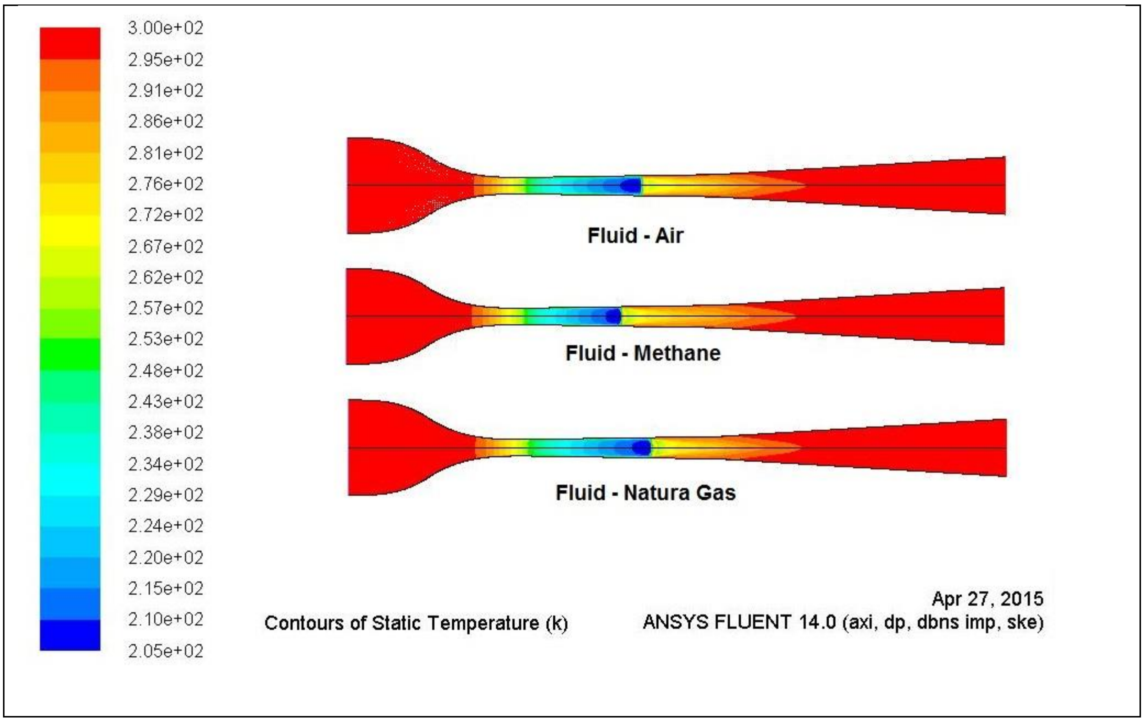


Figure: Temperature Contour Comparision for all the Simulations

6.7 Discussions

Shock Location:

Comparing all the simulation results it is being observed that the shock is generated in the divergent section of the supersonic separator. It is clearly noted that the shock is depending on the density of the fluid. For a lesser fluid density, the shock is generated more near to inlet. The table shows the location of the shock produced in the supersonic separator when different fluids are introduced.

Table: Shock Location

Fluid	Density (Kg/m^3)	Shock Location (from inlet)
Air	1.09	321 mm
Methane	0.62	288 mm
Natural Gas	0.66	317 mm

Pressure Drop:

The Pressure drop plays a crucial role in defining the efficiency of the supersonic separator. Due to expansion process in the nozzle the pressure gets to minimum. The nucleation process starts because of this pressure drop. The angle of diffuser should be such that it should achieve the targeted recovery pressure. In this case when natural gas is passed through the fluid, the pressure drop had reached the lowest. The recovered pressure drop is more in case of methane simulation.

Table: Pressure Variations

Fluid	Pressure Drop	Recovered Pressure Drop
Air	20%	70%
Methane	23.58%	75%
Natural Gas	19.45%	70%

Mach number Variation:

The Mach number variation id depended on the fluid velocity. In this case the axial velocity is depending on the throat area. The axial velocity is derived from the pressure variations given at the inlet. The Mach is found to be greater for high denser fluid. The maximum Mach number is obtained when air is passed through the nozzle.

Table: Maximum Mach number Location

Fluid	Max Mach	Location
Air	1.72	321 mm
Methane	1.63	288 mm
Natural Gas	1.70	317 mm

Temperature Change:

The temperature drop helps in condensing the fluid. Before the shock position the temperature reaches to its minimum due to expansion and suddenly increases due to the shock effect.

Table: Temperature variation at the shock location

Fluid	Max Temp ^{o}K	Min Temp ^{o}K	% Variation
Air	286.04	205.45	71%
Methane	279.48	215.25	77%
Natural Gas	272.91	192.26	70%

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1.0 INTRODUCTION Natural gas which is transmitted in subsea pipelines need to be dehydrated to ensure smooth operation of gas transmission. The liquid water in pipelines may condense and accumulate at low points along the pipeline reducing its flow capacity. [2] The mixture of liquid and gas might cause liquid hammering in the pipelines and may damage the equipment's especially the rotating equipment's. In order to overcome the transmission problems in pipelines a supersonic separator has been introduced. The supersonic separator processes the natural gas for condensation and separating water from heavier hydrocarbons. 1.1 Supersonic Separator This supersonic separator combines the thermo -dynamics, fluid -dynamics