Thermo-compressor : Design and CFD Analysis for Sugar Factory

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Thermo-compressor : Design and CFD Analysis for Sugar Factory

Major Project

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(Thermal Engineering)

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Declaration

This is to certify that

1. The Thesis comprises my original work toward the degree of Master of Technology in Thermal Engineering at Institute of Technology, Nirma University and has not been submitted elsewhere for a degree.

2. Due to acknowledgment has been made in the text to all other material used.

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I,Mehul Chhowala, Roll No.12MMET06 , give undertaking that the Major Project entitled **"Thermo-compressor:Design and CFD Analysis for Sugar Factory"** submitted by me, towards the partial fulfillment of the requirements for the degree of Master of Technology in Mechanical Engineering(Thermal Engineering) of Nirma University, Ahmedabad, is the original work carried out by me and I give assurance that no attempt of plagiarism has been made. I understand that in the event of any similarity found subsequently with any published work or any dissertation work elsewhere; it will result in severe disciplinary action.

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Abstract

Thermo-compressor is design to recirculate steam or boost lower-pressure steam for reuse in a variety of process applications in pulp and paper, petrochemical, food processing, desalination, and specialty chemical production.In thermo-compressor, lower-pressure steam mix with higher-pressure steam. The higher-pressure motive steam entrains the lower pressure steam and increases its pressure.The motive steam is introduced through the nozzle of the thermo-compressor.In this part of study,sugar factory data was collected from chalthan sugar factory for design calculation and CFD analysis.

Boiler data has been used for calculation of primary nozzle design and turbine exhaust data used for suction chamber as waste steam or low-pressure steam.By using the gas-dynamic compressible flow theory and design methodology of thermo-compressor, major dimension was found for CFD analysis. Firstly, a numerical method has been implemented to evaluate Mach number of supersonic nozzle. The results have been validated using theoretical calculation data.

Detail design of thermo-compressor is validated by CFD software ANSYS CFX and same is validated with performance of the same reported in various literature.The parametric study with nine different boundary condition of secondary pressure of thermo-compressor analysis is carried out.The effect of pressure of secondary flow on Exit pressure,Mach number and velocity also presented.

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Nomenclature

E	Total energy (Nm)
g	gravitational acceleration (m/s^2)
m	mass flow rate (kg/sec)
P	Static pressure (bar)
P_0	Stagnation pressure (bar)
T_0	Stagnation temperature (K)
q	mass flux over boundaries (kg/sm^2)
t	time (sec)
T	statis temperature (K)
u	velocity component (m/s)
x	independent variable
y	dependent variable
z	axial coordinate
CR	Compression ratio
ER	Entrainment ratio
α	converging angle (Degree)
μ	dynamic viscosity (Ns/m^2)
ρ	density (kg/m^3)
τ	stress tensor
dis	discharge flow
mot	motive flow
suc	suction flow

Chapter 1

Introduction

To increases the pressure of steam or for re circulation of steam,thermo-compressors are used.This pressurized steam is used in many applications,usually for process industries like chemical industries,paper industry and for desalination.To increase the pressure of low pressure steam,high pressure,normally termed as motive steam is used.Motive steam boost the low pressure steam.This leads in the increase of pressure.Motive steam flow rate is kept higher and usually a convergent-divergent nozzle is used to supply this steam.Hence thermo-compressor has two convergent-divergent nozzle.

1.1 Application of Thermo-compressor

In general, Thermo-compressors, steam ejectors, exhausters or jet pumps, as they are called sometimes, are widely used in many industrial fields.Now a days paper industry around the world are converting their conventional system to that of a thermo-compressor with flash steam recovery.A large saving in cost in sugar industry is witnessed when vapour is en compressed from the last stage of multi-stage evaporaters.Most industries use captive power plants to satisfy their power needs.The low pressure steam from exhaust of turbine can be re-pressurized and used in distillation process. Also,similar arrangement can be made in petrochemical industries and steam can then be used for drying and distillation process.Normally,steam is re-used in boilers during the bulk drug production.Thermo-compressor can be used in such applications.Thus,if low pressure steam is available,thermo-compressor can be used to increase the pressure of steam and then can be re-used for useful operations. The main advantage of steam ejectors is that they have no pistons, valves, rotors, or any other moving parts, no lubrication or oil problems, nor extremely close tolerances and hence require little maintenance. Thermo-compressor have many applications, such as heating, humidifying and pumping toxic and solids-bearing fluids, where a mechanical pump may be unsuitable.

1.2 Principle of Thermo-compressor

The motive steam, discharges from a high pressure region through a nozzle into a low pressure zone, developing a high velocity jet at low pressure for moving the fluid into the mixing chamber, (i.e. the convergent section of the diffuser).The motive steam mixes with the second flow entering the mixing chamber (i.e. the parallel sections of the diffuser).The mixture flows through the divergent part of the diffuser to be discharged at a higher pressure than in the mixing chamber and the velocity is reduced and discharge pressure recovered.

1.3 Geometry of Thermo-compressor

A schematic view of various zones of a thermo-compressor with steam flow is shown in Fig. 1.1. Thermo-compressor have four major zones:

- Motive nozzle.
- Converging portion.
- Zone of Constant area.
- Zone of Diffusion.

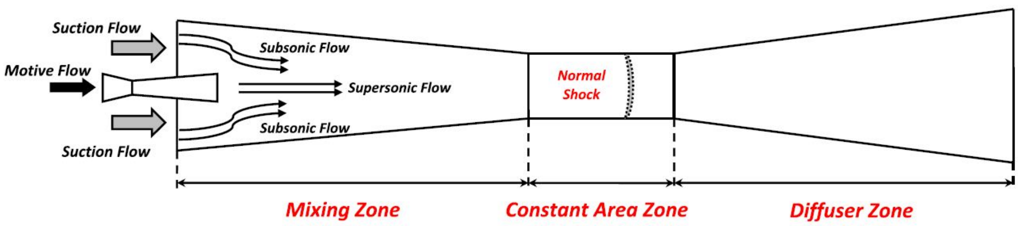

Figure 1.1: various zones and streams of thermo-compressor.[2]

Thermo-compressor consist of a small motive nozzle,usually a convergent-divergent type,kept within a shell or casing.The shell or casing is also convergent-divergent type. The exit of motive nozzle is placed in the convergent portion.The high pressure steam from motive nozzle and low pressure steam are allowed to mix in the convergent portion. Therefore,this portion is called the mixing zone.The zone of constant area is called throat.Shock wave occurs in this zone.The mass flow rate is controlled in this zone and therefore this becomes the most important portion of thermo-compressor.

The zone of diffusion also called diffuser which recovers the static pressure of the exit flow.The high pressure steam is inserted through motive nozzle.This zones effect is supersonic with very low static pressure.Due to viscous flow effect,the main flow traps the surrounding flow.This leads to low static pressure at exit of nozzle.This phenomenon creates suction.This type of vacuum exist even when secondary inlet is closed.The secondary flow therefore mixes with primary flow.Due to high momentum transfer,the secondary is accelerated and high static pressure is recovered and leads to high pressure at outlet of thermo-compressor.

1.4 Thermo-compressor flow phenomemon

Three distinct streams exist at thermo-compressor as illustrated in Fig.1.1 These flows are as follow:

- Motive nozzle flow(primary nozzle flow): The high pressure and temperature steam enters the thermo-compressor by the primary nozzle.
- Suction flow(secondary flow): The low pressure and temperature stream is trapped in the mixing chamber. This flow is compressed due to the kinetic energy of primary nozzle flow.
- Diffusion flow(outlet flow): The mixed stream of two previous flows which is delivered to the exit of thermo-compressor with a higher pressure than secondary flow(pressure).

Suction flow is accelerated to sonic velocity by the momentum of the primary nozzle flow and mixes with secondary flow in the mixing portion. The mixing between both flow continues well beyond the converging portion and choking occurs at the end of the constant area portion(i.e. the throat of thermo-compressor). Hence, the mixed flow becomes subsonic through a strong shock and the kinetic energy is converted into pressure. After that, the mixed flow is more expanded to a higher static pressure in the diffuser portion.

1.5 Thermo-compressor characteristics and performance curve

"Entrainment Ratio"(ER)called non-dimensional mass flow rate and "Compression Ratio" (CR) called non-dimensional pressure.These parameters are defined as follows:

$$ER = \frac{m_{suc}}{m_{mot}} \tag{1.5.1}$$

$$CR = \frac{P_{dis}}{P_{suc}} \tag{1.5.2}$$

The higher the ER and CR, the better the performance of the thermo-compressor.ER and CR are inversely proportional.These parameter when plotted against each other gives the characteristic of thermo-compressor shown in Fig.1.2.The performance curve defines thermo-compressor in terms of flow parameter or behaviors.Accordingly the thermo-compressor is divided in three distinct categories.

- Stable operation(Double choked flow)
- Semi-stable operation(Single choked flow)
- Reversed flow operation(Malfunctioning)

Secondary flow when is choked in constant area zone,the outlet pressure is less that the exit pressure.This makes the ER constant(horizontal line on performance curve).This suggest the stable operation of thermo-compressor if outlet pressure is greater than critical pressure,the value of ER drastically decreases.This is due to unchoked secondary flow at throat.The higher value of P_{dis} leads to drop in ER and the corresponding effect is to reverse the flow in mixing zone.The compression of low pressure stream is drastically reduced.Therefore for steady operation,thermo-compressor should be operated in stable condition(i.e double choked flow)

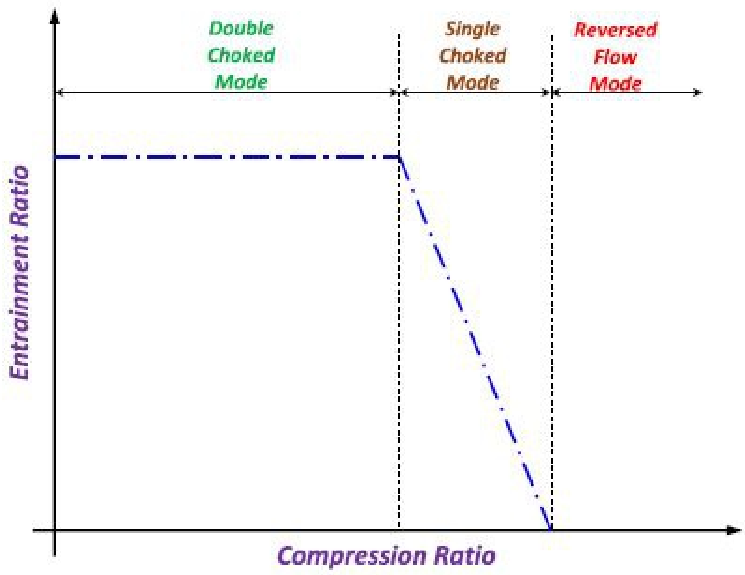

Figure 1.2: Thermo-compressor performance curve.[2]

1.6 Thermo-compressor shape parameter

- Motive nozzle throat diameter (D_{th}).
- Mixing zone inlet diameter (D_m).
- Constant area length (L_c).
- Constant area diameter (D_c).
- Diffuser portion outlet diameter (D_d).
- Diffuser portion length (L_d).

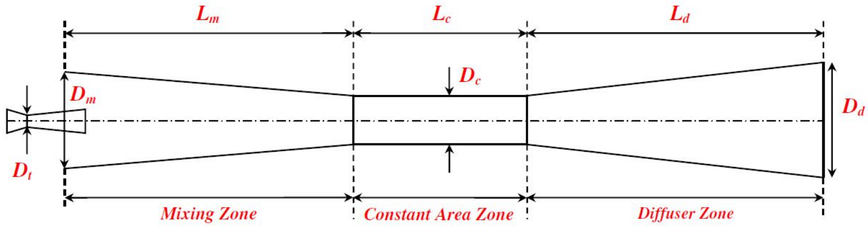

Figure 1.3: Cross section of the thermo-compressor with important shape parameters.[2]

1.7 Outline of Thesis

Basic introduction,application,principle,flow phenomenon and shape parameter about thermo-compressor described in **chapter 1.**

Chapter 2 deals with literature review of researches that carried out in the field of thermo-compressor.

Chapter 3 deals with basic design methodology about thermo-compressor and step by step calculation for sugar factory data case.

In **Chapter 4** represent the numerical scheme which applying in CFD analysis and contains result of CFD analysis & discussion of achieved analysis result of parametric study of thermo-compressor.

Chapter 5 shows Conclusions and future scope of thesis.

Chapter 2

Literature Review

Navid Sharifi and Masoud Boroomand[1] concluded that The CFD analysis results are negligible between axi-symmetric and 3-D simulations. It means that the axi-symmetric modeling of thermo-compressor is very accurate, and it is not required to use a full 3-D analysis for further studies.A numerical model was obtained during this study. This analysis tool can be used to study the effects of different dimensional parameters of the thermo-compressor on the performance aspects, which will be explained in the next part.

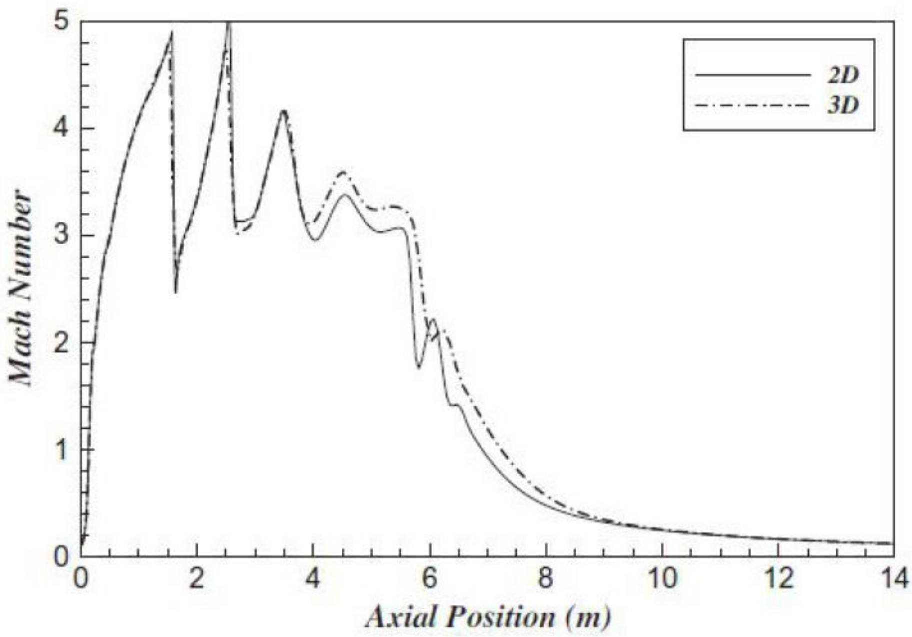

Figure 2.1: Mach-number along the axis of the thermo-compressor.[1]

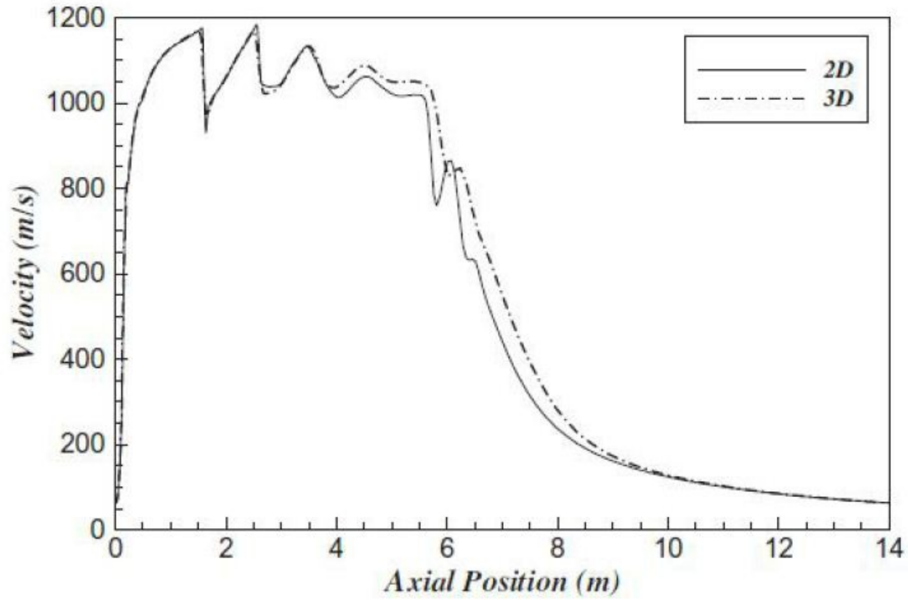

Figure 2.2: Velocity along the axis of the thermo-compressor.[1]

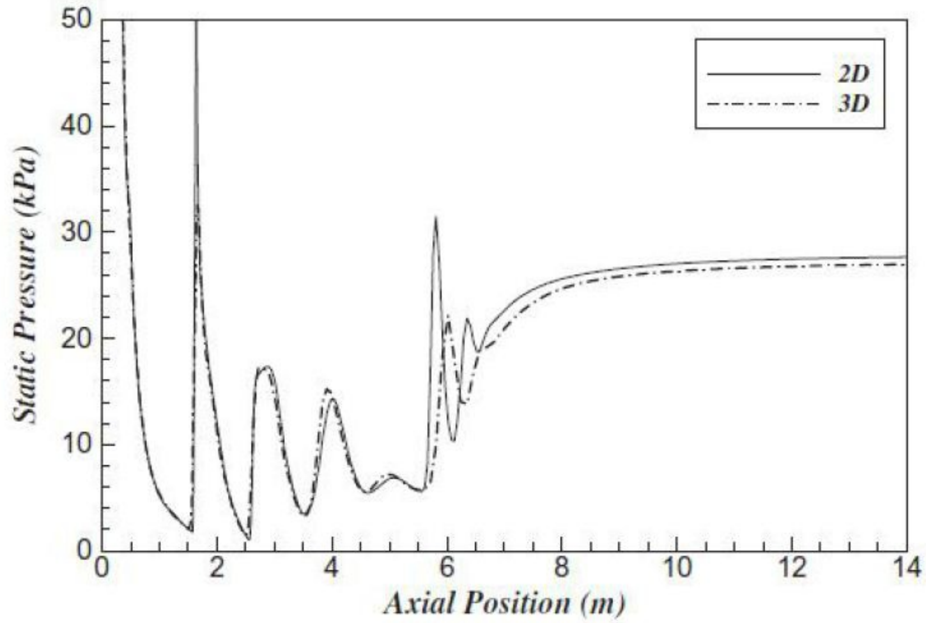

Figure 2.3: Pressure along the axis of the thermo-compressor.[1]

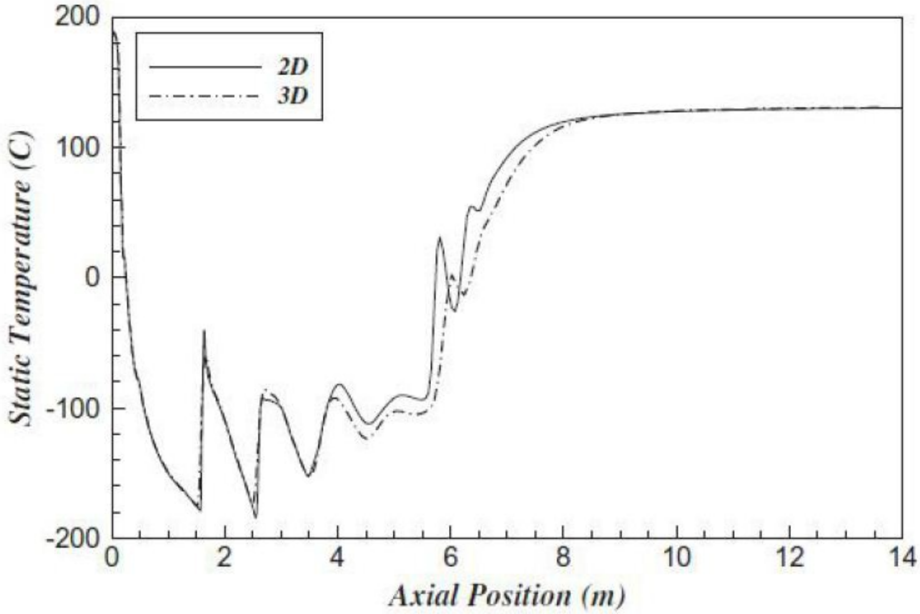

Figure 2.4: Temperature along the axis of the thermo-compressor.[1]

In second part of Navid Sharifi and Masoud Boroomand[2] study published a new relationship between important shape parameter and performance of a thermal-compressor is derived.Advantage of the this technique is that the design methodology introduced here,as the results of time-consuming CFD analysis is compressed in comprehensive design charts sets.

Two dimensionless parameters related to the mixing zone shape parameter are introduced (i.e. V' and L/D),in this study.Dimensionless volume (V') has not been defined before.A new equation derived which equate to the dimensionless characteristic parameters to dimensionless shape parameters. The equation can be used to determined the maximum value of ER for a given value of L/D.The actual model of thermo-compressor was build up experimentally based on the this design methodology and checked successfully.

T. Sriveerakul,et. al[3] represent that the CFD analysis results can efficiently to explained the flow phenomenon inside the steam ejector.Good understanding of the flow phenomenon inside the ejector is needed to increase the performance of an ejector. In this study,CFD was used to analyze the flow phenomena inside a steam ejector. According to the validation of the static pressure profile along the wall of the ejector ,ER , and critical back pressure as was carried out.

As the high temperature and pressure primary nozzle fluid enters the convergent portion, the subsonic flow accelerates to sonic flow and chokes occurs at the nozzle throat. In the divergent section of the nozzle, the primary nozzle fluid accelerates and expands further to achieve a supersonic speed. At the exit plane of ejector, it is found that static pressure higher than pressure of the mixing chamber.

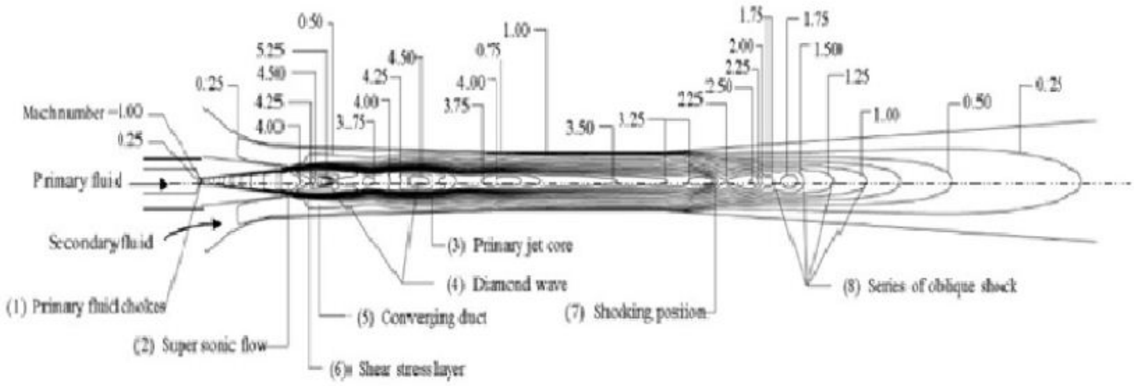

Figure 2.5: contours line of mach number in steam ejector.[3]

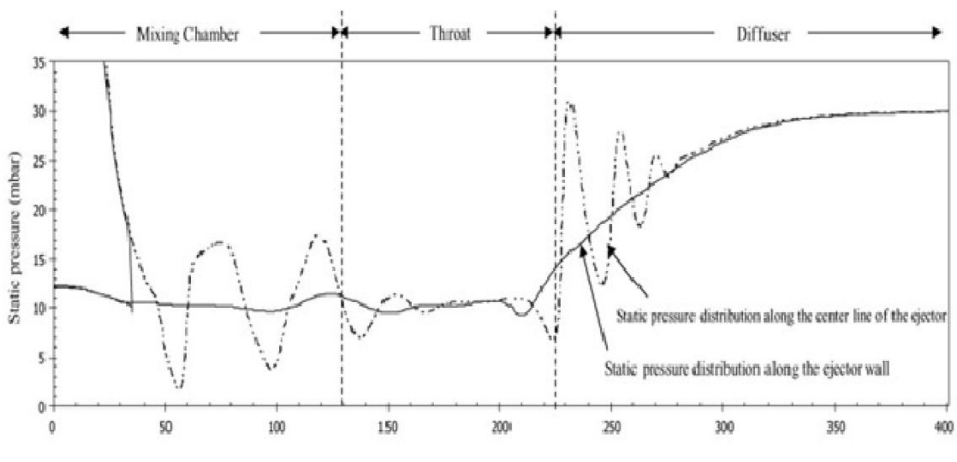

Figure 2.6: Static pressure along the steam ejector.[3]

MyoungKuk Ji et. al[4] studied that CFD analysis is to find the flow phenomenon and performance of an ejector. The ejector performance were at effect of various operating pressure. Ejector shapes, expressed by the angle of converging duct, were also changed and the ejector performance was carried out.The CFD analysis results were validated with the experimental results.CFD analysis was of great benefit in the study because it explained phenomenon inside the ejector in detail.

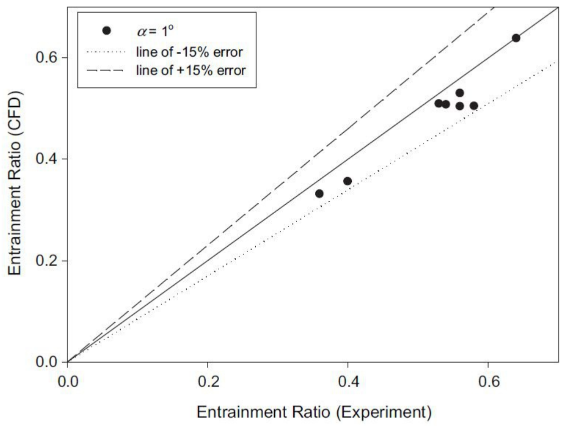

Figure 2.7: Comparison of ER for CFD analysis and experimental results.[4]

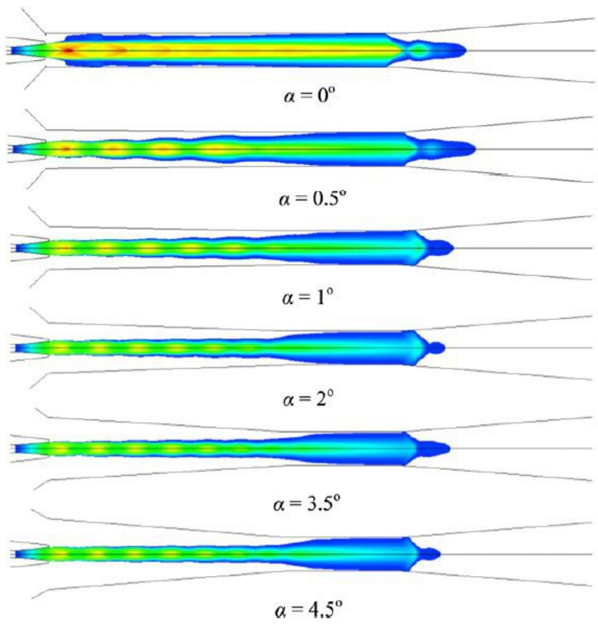

Figure 2.8: Effect of angle of converging on the contours of Mach num.[4]

Kavous Ariafar[5] represent that the CFD is an efficient tool to estimate the entrainment ratio ad critical back pressure of the thermocompressor for different operating conditions. It also helps to reveal the phenomena inside the thermocompressor in details. According to the obtained results, for practical purposes, the best way to increase the entrainment ratio for an installed thermocompressor in an industry is to decrease the pressure of motive steam.Results also indicated that increasing the Mach number at the nozzle exit plane does not affect the thermocompressor performance but it will increase the critical back pressure.

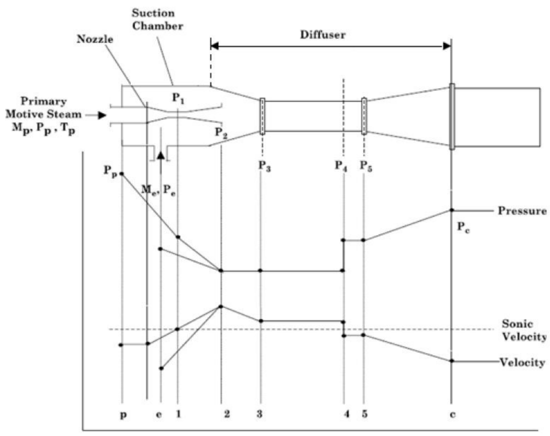

Figure 2.9: Schematic of the thermocompressor with pressure-velocity profile along the axis.[5]

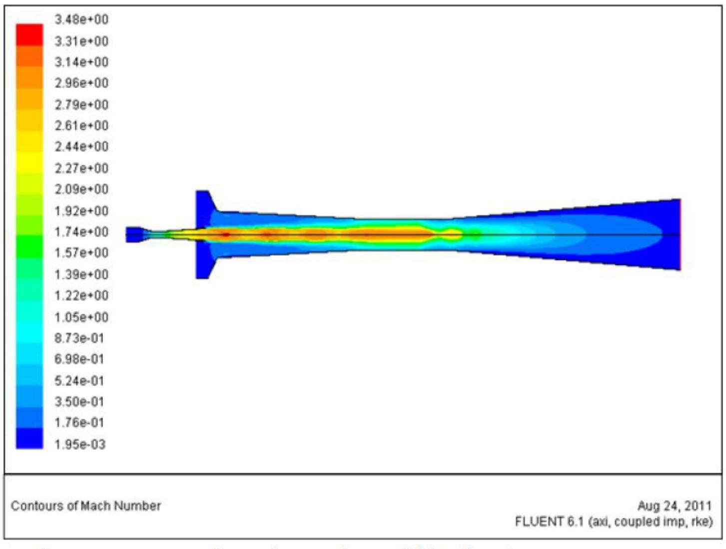

Figure 2.10: Contours of Mach number within the thermocompressor.[5]

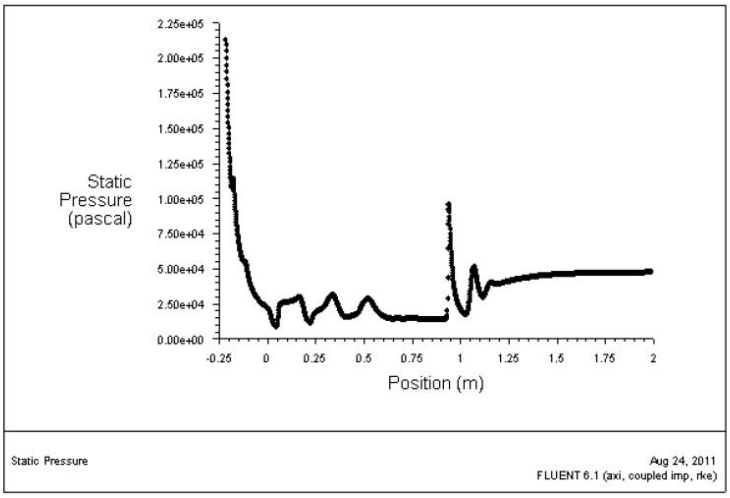

Figure 2.11: Static pressure profile along the thermocompressor axis.[5]

H. C. Man, J. Duan and T. M. Vue[6] gives the design procedure of supersonic nozzle which give high velocity and mach number at exit of nozzle The design is based on the theory of gas dynamics in that the potential energy of high stagnation pressure is converted totally into effective velocity energy so that a high momentum of the exit jet.

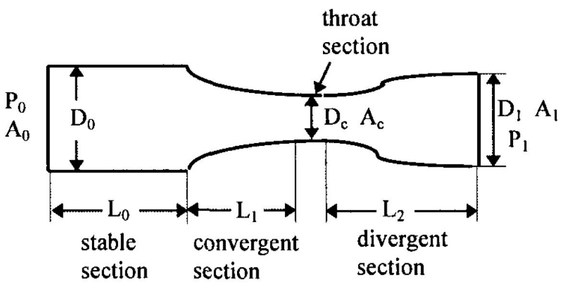

Figure 2.12: Conceptual diagram of a supersonic nozzle.[6]

Chapter 3

Design methodology of thermo-compressor

3.1 Basic design procedure

Design if thermo-compressor is based more or less on traditional design of ejector.Nozzle throat diameter(D_{th}) and constant throat diameter(D_c) are the main unknown parameter in the design of thermo-compressor.Nozzle throat diameter gives the idea about total steam required for motive purpose,i.e its mass flow rate and finally the pressure of delivery flow.The consumption and delivery are dependent on the below mentioned parameter.

- Steam rate entering motive nozzle (m_{mot})
- Production rate of steam required ($m_{delivery}$).

The maximum flow rate condition is the choking condition at the throat.Therefore,the size of the thermo-compressor actually determines the delivery steam flow rate.Using the equation of isentropic flow,the mass flow rate for choked condition of nozzle can be written as:

$$m = \left(\frac{P_0 A}{\sqrt{RT_0}}\right)\left[M\sqrt{\gamma}\left(1+\frac{\gamma-1}{2}M^2\right)\right]^{\frac{\gamma-1}{2-2\gamma}} \tag{3.1.1}$$

At choked condition,the sonic velocity condition exist,i.e.Mach number=1 at throat. Assuming constant specific heat capacity γ=1.33,the above relation can be use to determine A_{th} and A_c.

- To calculate (A_{th})(i.e throat area of supersonic nozzle),the total pressure (P_0), total temperature (T_0) and motive steam consumption rate is used.

- if (A_c) is unknown,with the down stream condition fixed,the values of P_0, T_0 and m_{dis} can be reused.This would give a value of throat area that is unique.

1D gas dynamics can be used to find the mixing length,diffuser length and the position of nozzle once the values of D_c and D_{th} are evaluated.Many researcher suggested ranges for length and angles.But best performance is not assure.This is became a combination of shape,length and angle is to be a selected.The values proposed for mixing zone length and converging angle are summarized below.

- Mixing zone length (L_m):5 to 10 times of (D_c) [5].

- Converging angle of mixing section: 5 to 8[7].

To decide the performance of designed thermo-compressor,the numerical siulation would be advantageous.Numerical simulation can lead to better design as good CFD analysis would reduced the cost and would present unnecessary experimental trials.Once design is checked numerically,the thermo-compressor can be experimentally analyzed. Therefore the design approach must be to use various combination of sizes,analyze each design using CFD methods and then evaluate the best design experimentally.

3.2 Non-dimensional shape parameters

The geometrical variations in terms of size and shape can be incorporated by defining non-dimensional parameter.

$$V_{mix} = \frac{\pi}{12} L_m \left(D_c^2 + D_c D_m + D_m^2 \right) \tag{3.2.1}$$

Mixing zone shape is a cone with parameter of mixing length,mixing zone diameter and constant area diameter.the volume of mixing zone is the volume of cone evaluated as in equation.

Dimensionless mixing length (L/D) is the ratio of L_m to D_c.

$$\frac{L}{D} = \frac{L_m}{D_c} \tag{3.2.2}$$

Dimensionless mixing volume (V') is the ratio of V_{mix} to D_c.

$$V' = \frac{V_{mix}}{D_c} \tag{3.2.3}$$

For CFD analysis,the values of D_{th} and D_c are fixed and boundary condition s are fixed.

3.3 Procedure for geometry variations

The selection of based geometry for thermo-compressor is based on evaluating the performance of each geometry and then comparing to deduce the best geometry.Each shape meters are to the varied arbitarily.In the present work one value of V' is selected.the geometry is numerically analyzed.The steps used to vary the preliminary dimensions are below:

- Using eq.3.1 calculate thermo-compressor throat diameter (D_c).
- Select value of non-dimensional volume (V').
- Evaluate (V_{mix}).
- Assume value of (D_m).
- Evaluate (L_m).
- Create the thermo-compressor geometry.
- Produce computational grid for thermo-compressor.
- Apply flow solver under given boundary condition.
- Obtain a converged solution.

3.4 A step by step calculation for sugar factory case.

In this part, a case study for the size selections based on the above design methodology is introduced.

Step (1): Assume fixed boundary conditions.

- Available motive steam: total pressure of 31.36 bar,temperature of 380-390 C with consumption rate of 45 ton/h.
- Secondary flow: total pressure of 1 bar, total temperature of 350-390 C.
- Delivery or Exit flow: total pressure of 3 bar and maximum allowable delivery rate of 30 ton/h.

Step (2): Evaluate D_{th}.

Substitution of P_0 =31.36 X 10^5 (Pa), T_0 = 653 (K) and mmot= 11.11kg/s in Eq. (3) is leading to D_{th} = 0.079 (m).

Step (3): Evaluate D_c.

Substitution of P_0 = 2.94 X 10^5 (Pa), T_0 = 405 (K) and mdis =8.33 kg/s in Eq. (3) is leading to D_c = 0.225 (m).

Step (4): Select the specific value of non-dimension volume (V')

Take V'=8 and D_c=0.225(m) in Eq.(6) get value of V_{mix}=0.091

Step (5): Assume arbitrary value of D_m

Take D_m=0.3(m)

Step (6): Evaluate L_m.

L_m=1.681(m)

Step (7): Create the thermo-compressor geometry.

Step (8): Produce computational grid.

Step (9): Apply flow solver under given boundary conditions.

Step (10): Obtain a converged solution.

Step (11): Evaluate the ER and CR from the CFD simulation results.

Table 3.1: Fixed parameter and boundary condition

	Pressure(bar)	Temperature(C)
Constant boundary condition		
1. Primary flow	31.3	380-390
2. Secondary flow	0.98	350-390
3. Discharge flow	2.94	-
Constant shape-parameter		
1. Nozzle throat diameter(D_{th})	0.079449(m)	
2. Constant area diameter(D_c)	0.22553(m)	

3.5 Supersonic nozzle design

In Thermo-compressor, primary nozzle having high velocity and mach number at exit. Therefore at the exit of primary nozzle mach number value is greater than one always which may be two or three. For supersonic nozzle we design initial condition like inlet Pressure, Temperature, mass flow rate and fixed the exit mach number.The gas dynamic theory suggest that potential energy of high stagnation pressure can be effectively converted to kinetic energy.The design of supersonic nozzle is based on the above criteria.This would give very high momentum at exit.

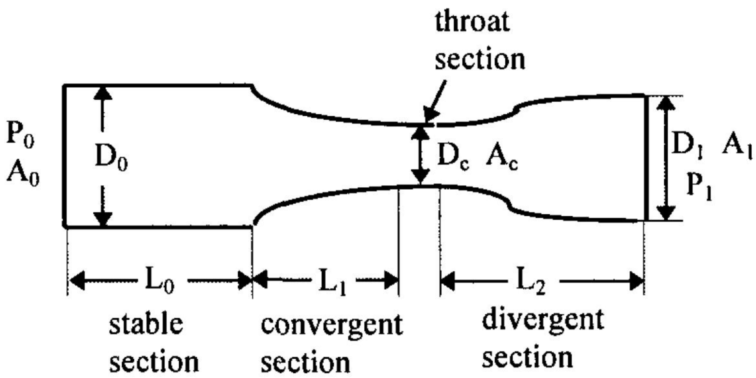

Figure 3.1: Conceptual diagram of a supersonic nozzle.[6]

According to the gas dynamics theory, we can determine the exit diameter, convergent section length and divergent section length of supersonic nozzle by fixing the exit mach number and convergent-divergent angle with suitable value which gives best results.

In sugar factory case data, assume exit mach number is 3 and select convergent-divergent angle are respectively 15^0 and 9^0.By calculation geometry parameters are as follow:

Table 3.2: Dimension of super-sonic nozzle

Parameter	Dimension(mm)
Nozzle throat diameter	79.447
Nozzle inlet diameter	152.4
Nozzle exit diameter	174.68
Inlet Mach number	0.06
Exit mach number	3
Convergent section length	277.085
Divergent section length	605.012
Convergent angle	15
Divergent angle	9

Fig.3.2 to 3.4 represent the geometry of supersonic nozzle,ANSYS geometry model and MESH model of supersonic nozzle.

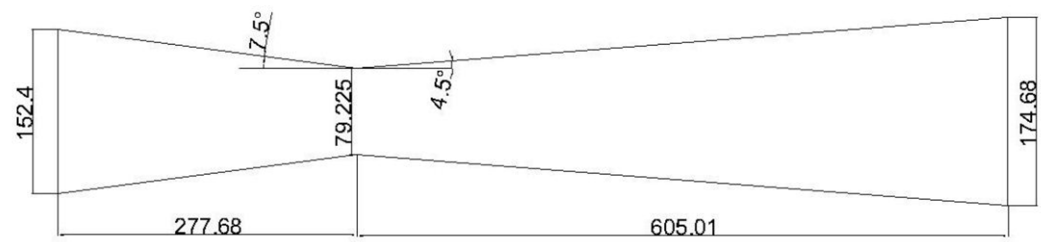

Figure 3.2: Geometry of a supersonic nozzle.

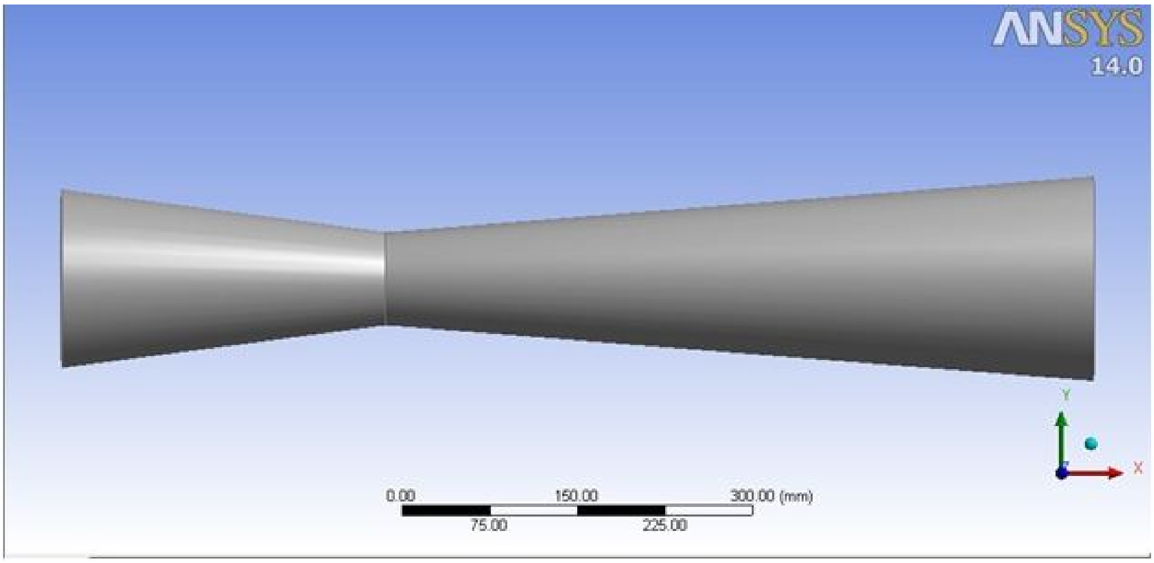

Figure 3.3: ANSYS geometry model of a supersonic nozzle.

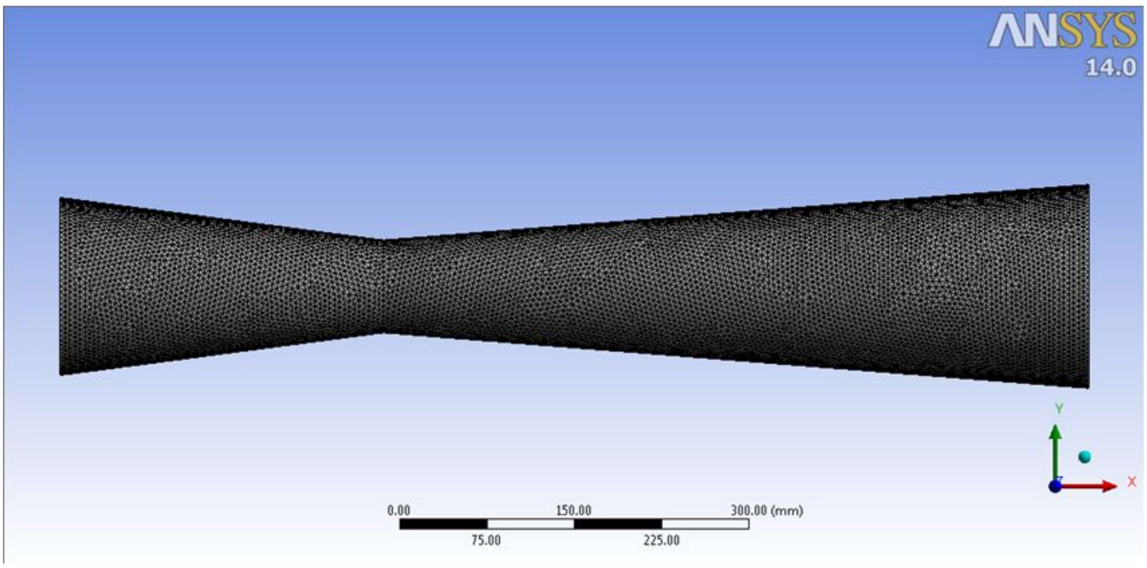

Figure 3.4: ANSYS Mesh model of a supersonic nozzle.

3.6 Method of characteristic

The Method of Characteristics(MOC) is a numerical procedure for solving two- dimensional compressible flow problems.The method of Characteristics was developed by the mathematicians Jaques Saloman Hadamard in 1903 and by Tullio Levi-Civita in 1932.

The name comes from a method used to solve hyperbolic partial differential equations: Find "characteristic lines" (combinations of the independent variables) along which the partial differential equation reduces to a set of ordinary differential equations, or even, in some cases, to algebraic equations which are easier to solve.The applications of the method of characteristics for nozzle flows are not limited to the design of contours. The method may also be used to analyze the flow field inside a known contour as well.

To find the characteristic curve of supersonic nozzle,main require parameter is exit Mach number of nozzle and heat capacity ratio of stream.The procedure explained in appendix-1.

3.7 Selection of Supersonic nozzle

Supersonic nozzle plays prime importance to acquire high performance of thermo-compressor. To achieve high performance of thermo-compressor six different pressure ranges of supersonic nozzles are being taken for study,which lies between 32 to 22 kg/cm^2.

A "C" program is created to calculate all basic dimension and parameter for the particular pressure of supersonic nozzle.Output of this program gives area throat section,area of exit section,convergent length,divergent length,pressure at throat and pressure at exit section of supersonic nozzle."C" program script in appendix-2 and Fig. 3.5 show flow chart of program Fig. 3.6 represent the output of program.

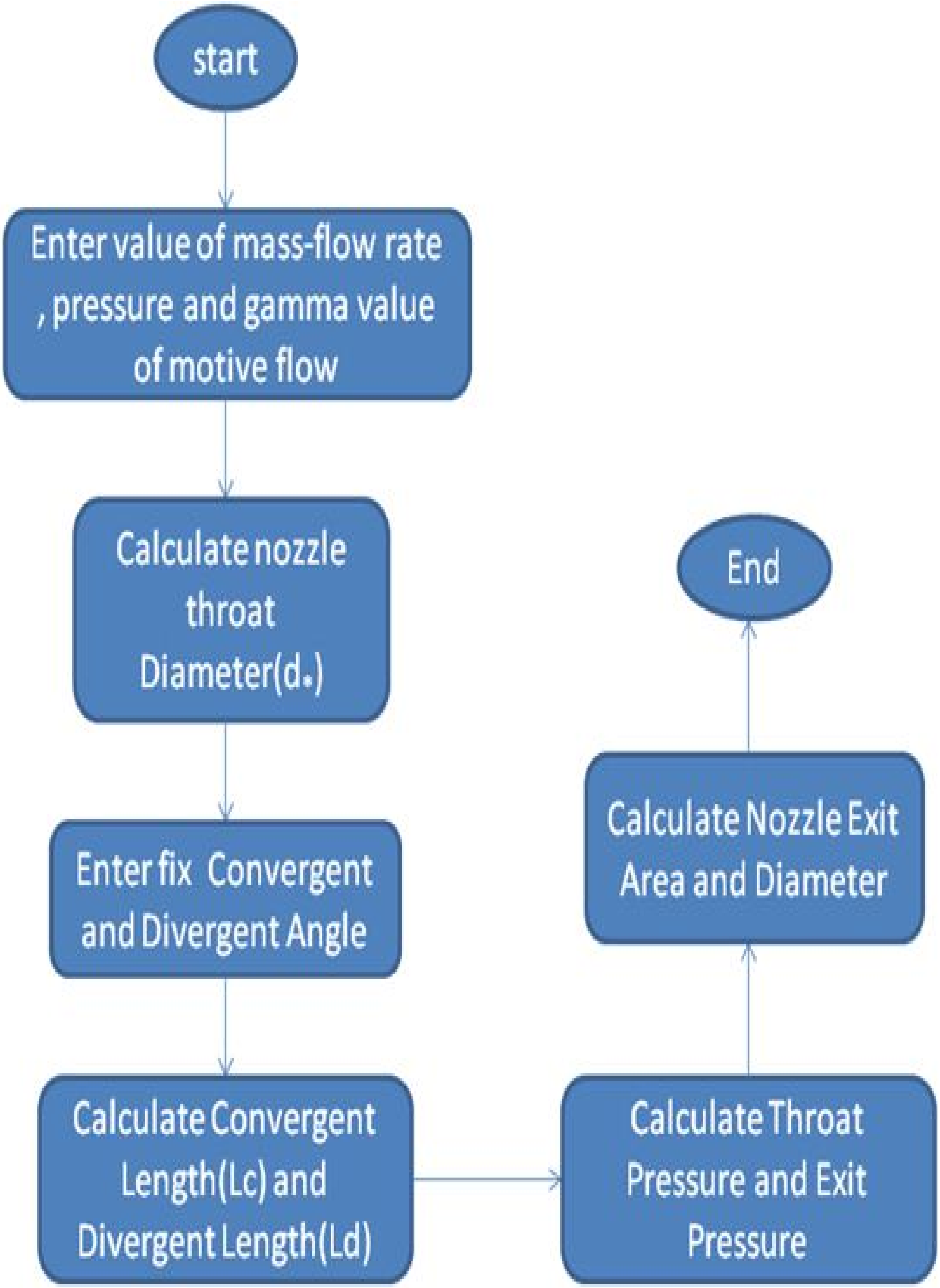

Figure 3.5: Flow chart of "C" program.

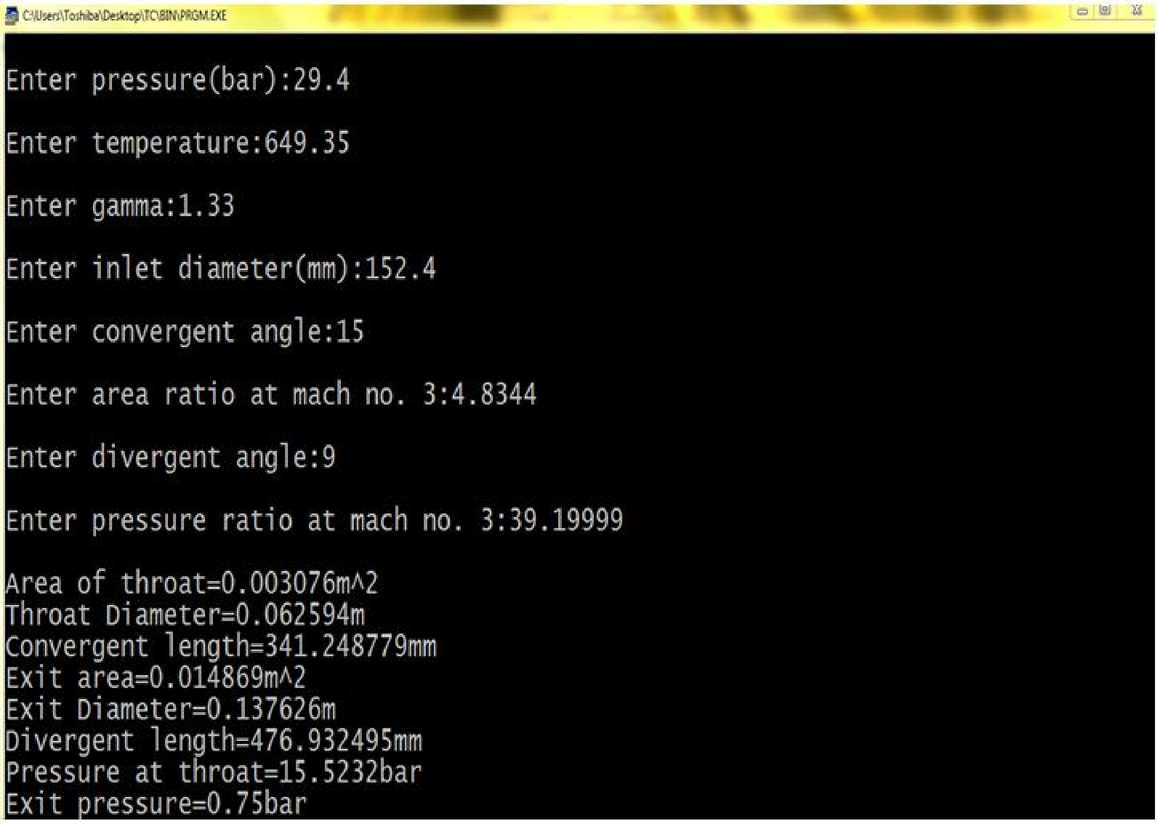

Figure 3.6: Output of "C" program.

Table 3.3: Nozzle parameter at different Motive Pressure

Motive Flow(kg/cm2)	Throat Dia.(mm)	Exit Dia.(mm)	Convergent Length(mm)	Divergent Length(mm)	Throat Pres.(bar)	Exit Pres.(bar)
32(31.36 bar)	60.67	133.40	348.35	462.08	16.55	0.80
30(29.5 bar)	62.59	137.76	341.24	476.93	15.52	0.75
28(27.44 bar)	64.69	142.25	333.250	492.971	14.48	0.70
26(25.48 bar)	67.04	147.40	324.53	510.81	13.45	0.65
24(23.52 bar)	69.66	153.17	314.377	530.81	12.41	0.60
22(21.5 bar)	72.64	159.71	303.07	553.48	11.38	0.55

Table 3.3 represent the dimensions of supersonic nozzle at six different motive pressure or primary nozzle pressure,which was used in selection of supersonic nozzle of thermo-compressor.

3.8 Design of thermo-compressor

The most important part of thermo-compressor is designing and selection of primary flow or supersonic nozzle.From the design procedure,dimensions of mixing zone inlet diameter(Dm),mixing zone length(Lm),constant diameter length (Lc),diffuser length(Ld)are as follow:

Table 3.4: Dimensions of Thermo-compressor

Parameter	Dimension(mm)
Mixing zone inlet diameter	300
Diffuser exit diameter	300
Constant area diameter	225.5
Mixing zone length	1681
Constant area length	1125
Diffuser length	1500

For complete analysis of thermo-compressor,supersonic nozzle of 22 kg/cm^2 is selected because inlet pressure of secondary flow is near to double of exit pressure of primary nozzle or supersonic nozzle.Geometry of thermo-compressor is shown in figure 3.7 and figure 3.8.Diffuser is located at 600 mm away from inlet of primary nozzle.

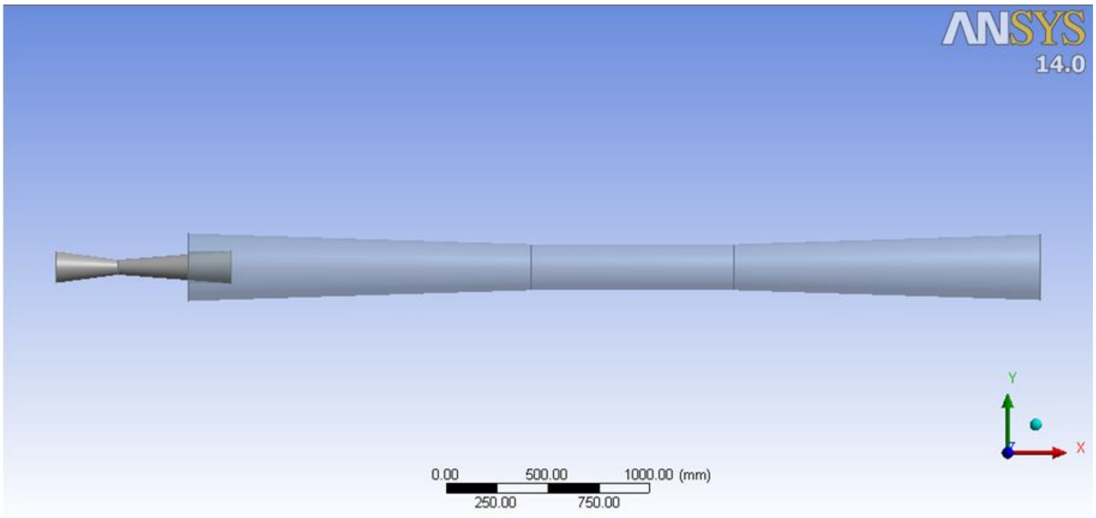

Figure 3.7: Geometry of a thermo-compressor.

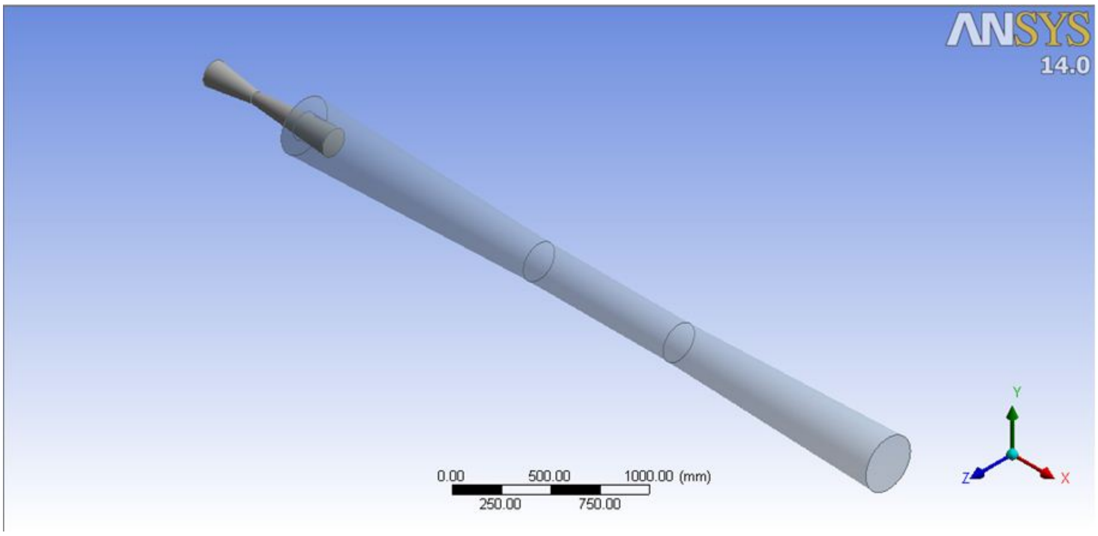

Figure 3.8: Geometry of a thermo-compressor.

Chapter 4

CFD Analysis of thermo-compressor

4.1 Numerical method

4.1.1 Numerical scheme

A ANSYS CFX(workbench 14.5) was used to study the behavior of flow within the thermo-compressor. By the transient density based method, the governing partial differential equation were solved.This approach was used because of highly compressible flow and high Mach number.The second order upwind scheme was used to discretize the convection term.To get accurate results, the residuals were expected to be at least 10^{-4}.The second order upwind discretization scheme is applied for all equations.[1]

4.1.2 Governing equation

The compressible flow in the thermo-compressor is governed by form of conservation equations. Previously, it was shown that the internal flow phenomenon can be modeled accurately through using axi-symmetric equations of flow motion.[2]The governing equations can be rewritten as follow:
Mass conservation equation

$$\frac{\partial \rho}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}(\rho r u_r) + \frac{\partial}{\partial z}(\rho u_z) = 0 \tag{4.1.1}$$

Momentum conservation equation

$$\rho\left(\frac{\partial u_r}{\partial t}+u_r\frac{\partial u_r}{\partial r}(\rho r)-\frac{{u_\theta}^2}{r}+u_z\frac{\partial u_r}{\partial z}\right)=-\frac{\partial p}{\partial r}+\rho g_r+\mu\left[\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial}{\partial r}(ru_r)\right)+\left(\frac{\partial^2 u_r}{\partial z^2}\right)\right] \tag{4.1.2}$$

$$\rho\left(\frac{\partial u_\theta}{\partial t}+u_r\frac{\partial u_\theta}{\partial r}(\rho r)+\frac{u_r u_\theta}{r}+u_z\frac{\partial u_\theta}{\partial z}\right)=\rho g_\theta+\mu\left[\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial}{\partial r}(ru_\theta)\right)+\left(\frac{\partial^2 u_\theta}{\partial z^2}\right)\right] \tag{4.1.3}$$

$$\rho\left(\frac{\partial u_z}{\partial t}+u_r\frac{\partial u_z}{\partial r}+u_z\frac{\partial u_z}{\partial z}\right)=-\frac{\partial p}{\partial z}+\rho g_z+\mu\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u_z}{\partial r}\right)+\left(\frac{\partial^2 u_r}{\partial z^2}\right)\right] \tag{4.1.4}$$

Energy conservation equation

$$\frac{\partial}{\partial t}(\rho E)+\bigtriangledown\cdot[\overrightarrow{u}\,(\rho E+p)]=\bigtriangledown\cdot[(k\bigtriangledown T)+(\tau\bigtriangledown T)] \tag{4.1.5}$$

$$\bigtriangledown\cdot\overrightarrow{u}=\frac{1}{r}\frac{\partial}{\partial r}(ru_r)+\frac{\partial}{\partial z}(u_z) \tag{4.1.6}$$

4.1.3 Turbulence modeling

It is necessary to consider reliable turbulence model.The mixing phenomenon of the two streams takes place in the viscous conditions. The realizable version of k-e turbulence model is used in this study. This turbulence model is used with the near-wall treatment as the “standard wall function” in this case. The internal flow of the thermo-compressor is assumed as a perfect gas (i.e.P = ρRT) in the domain.

4.2 Boundary condition

As discussed, there are two different flows enters in thermo-compressor beside a single outlet stream. The “pressure inlet” type boundary condition is applied to supersonic and suction flows, while the “pressure outlet” type boundary condition is applied for the thermo-compressor exit flow.The boundary conditions are listed in below Table.The values of input parameter in this table are stagnation values for in ANSYS.

Currently following CFD analysis done for only a secondary flow pressure at 1 kg/cm^2 (0.98 bar).After that several cases are taken for parametric study of thermo-compressor in the range 0.3 to 1.7 kg/cm^2 in the step of 0.2 kg/cm^2

Table 4.1: Boundary condition

Section	
Primary inlet pressure	21.56 bar
Secondary inlet pressure	0.98 bar
Diffuser exit pressure	2.94 bar
Exit Mass-flow rate	8.33 kg/s
Primary inlet temperature	634 K
Secondary inlet temperature	653 K

4.3 Geometry and grid study

Figure shows the thermo-compressor and supersonic nozzle geometries, with mesh elements in two-dimension.

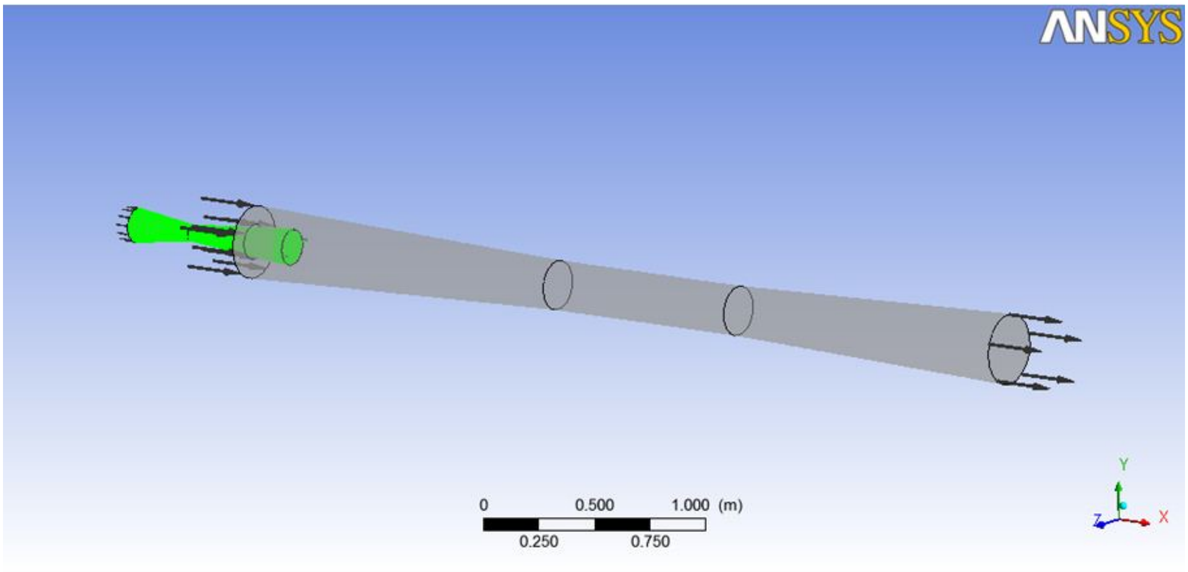

Figure 4.1: Geometry of a supersonic nozzle with meshing.

4.4 Parametric analysis of thermo-compressor

In parametric study of thermo-compressor,Nine different boundary conditions of secondary flow are taken.Three representative sace study of thermo-compressor with secondary inlet pressure.Case-I represent result of thermo-compressor when secondary inlet pressure is 0.49(0.5 kg/cm^2) bar,Case-II at secondary inlet pressure is 0.98 bar(1 kg/cm^2) and Case-III at secondary inlet pressure is 1.47 bar(1.5 kg/cm^2).

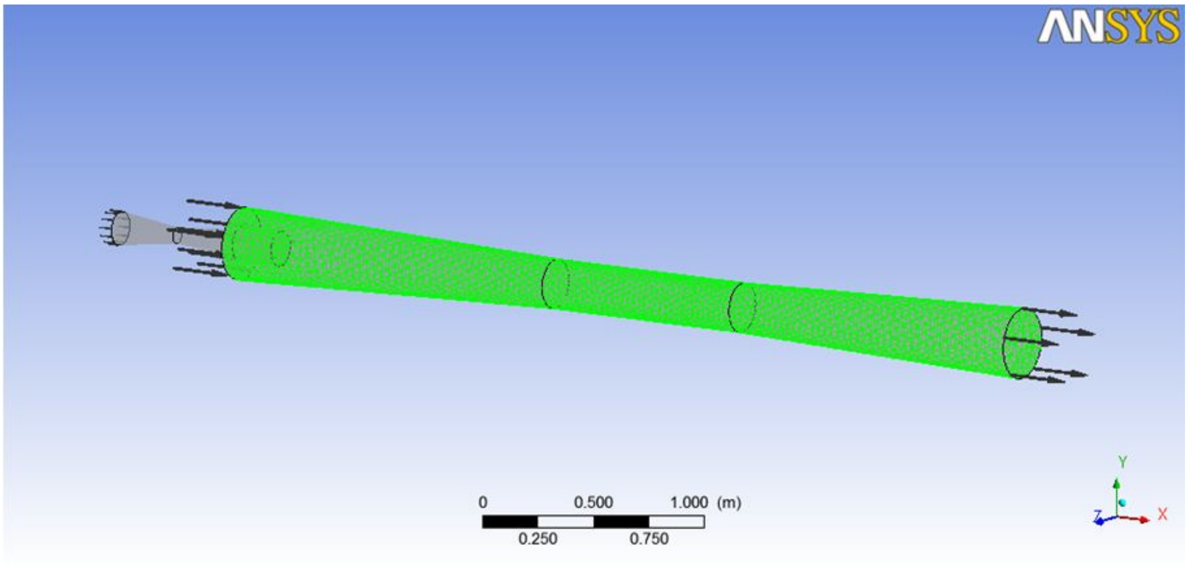

Figure 4.2: Geometry of a Thermo-compressor with meshing.

4.4.1 Case-1:Secondary inlet pressure=0.49 bar(0.5 kg/cm^2)

Figure 4.3,4.4 and 4.5 represent the variation of mach number contour,pressure contour and velocity contour along the longitudinal axis of thermo-compressor.

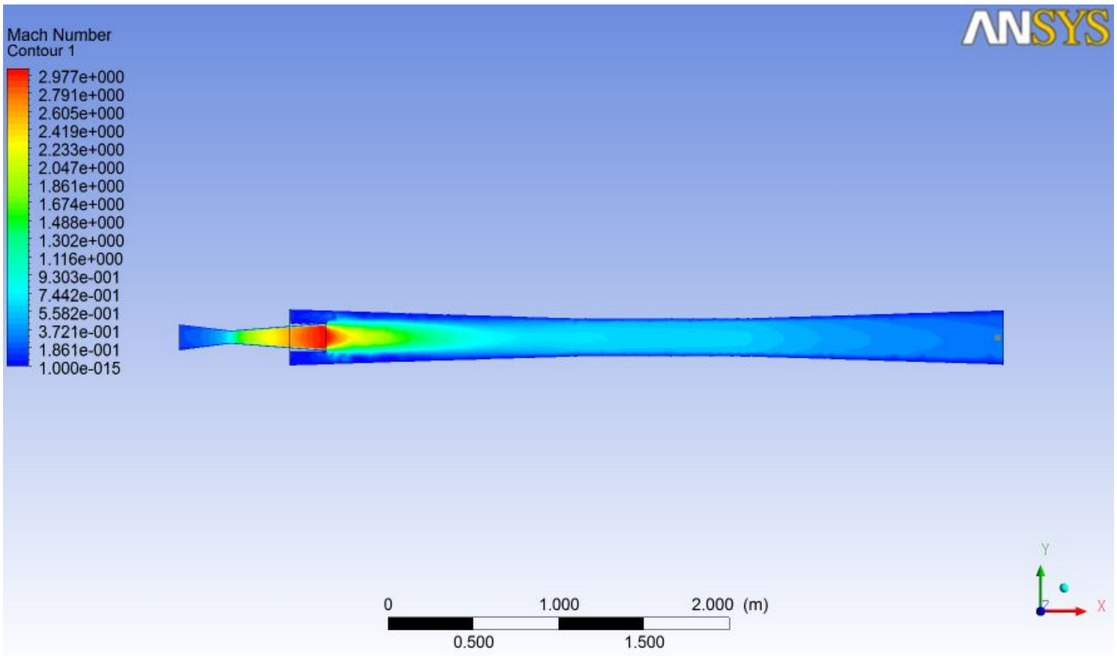

Figure 4.3: Variation of Mach number along longitudinal axis.

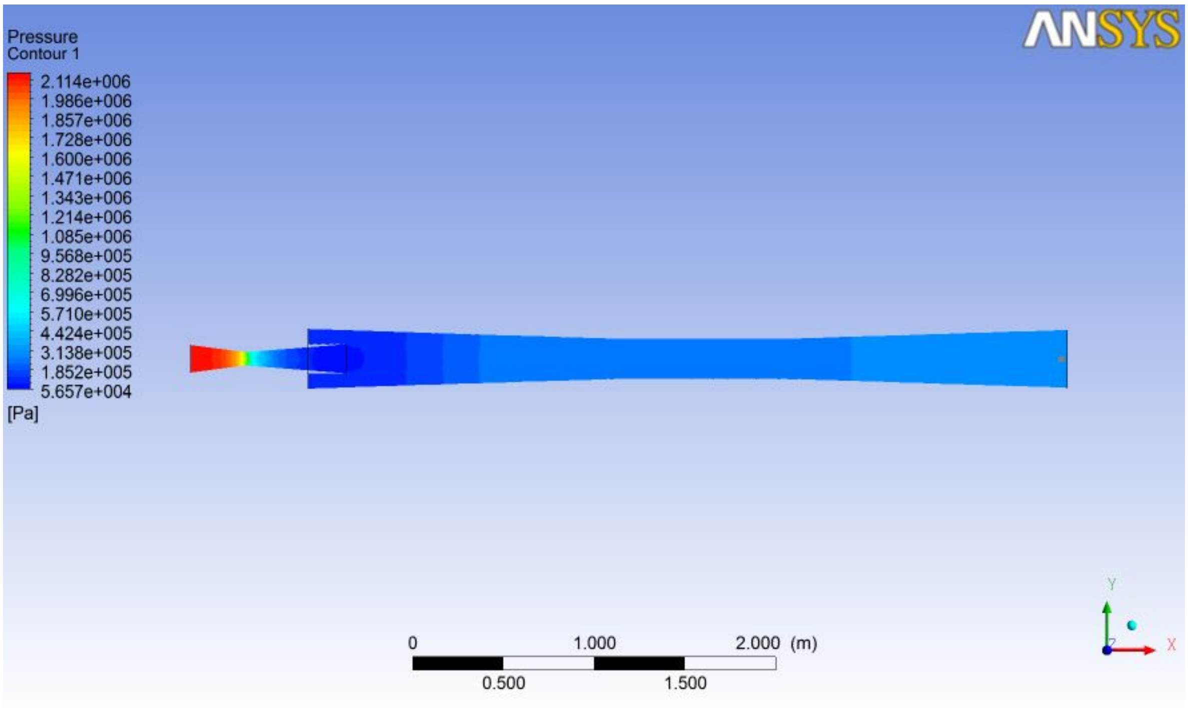

Figure 4.4: Variation of Pressure along longitudinal axis.

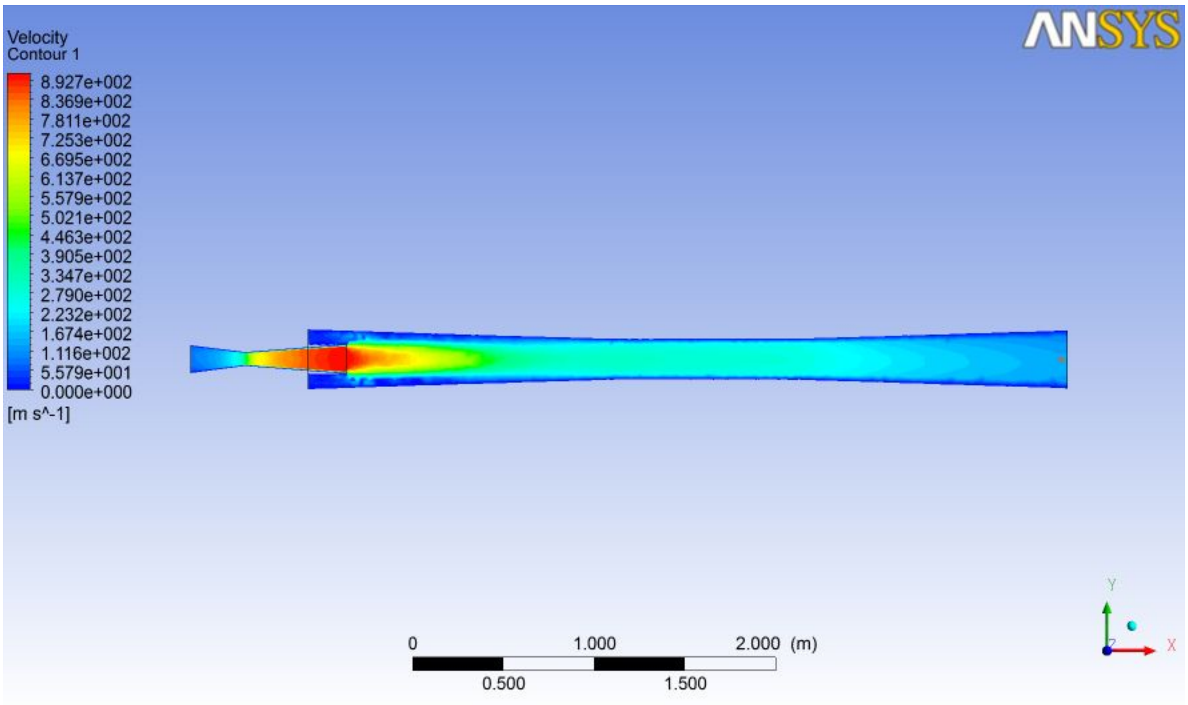

Figure 4.5: Variation of Velocity along longitudinal axis.

4.4.2 Case-2:Secondary inlet pressure=0.98 bar(1 kg/cm^2)

Fig. 4.6,4.7 and 4.8 represent the variation of mach number contour,pressure contour and velocity contour along the longitudinal axis of thermo-compressor.

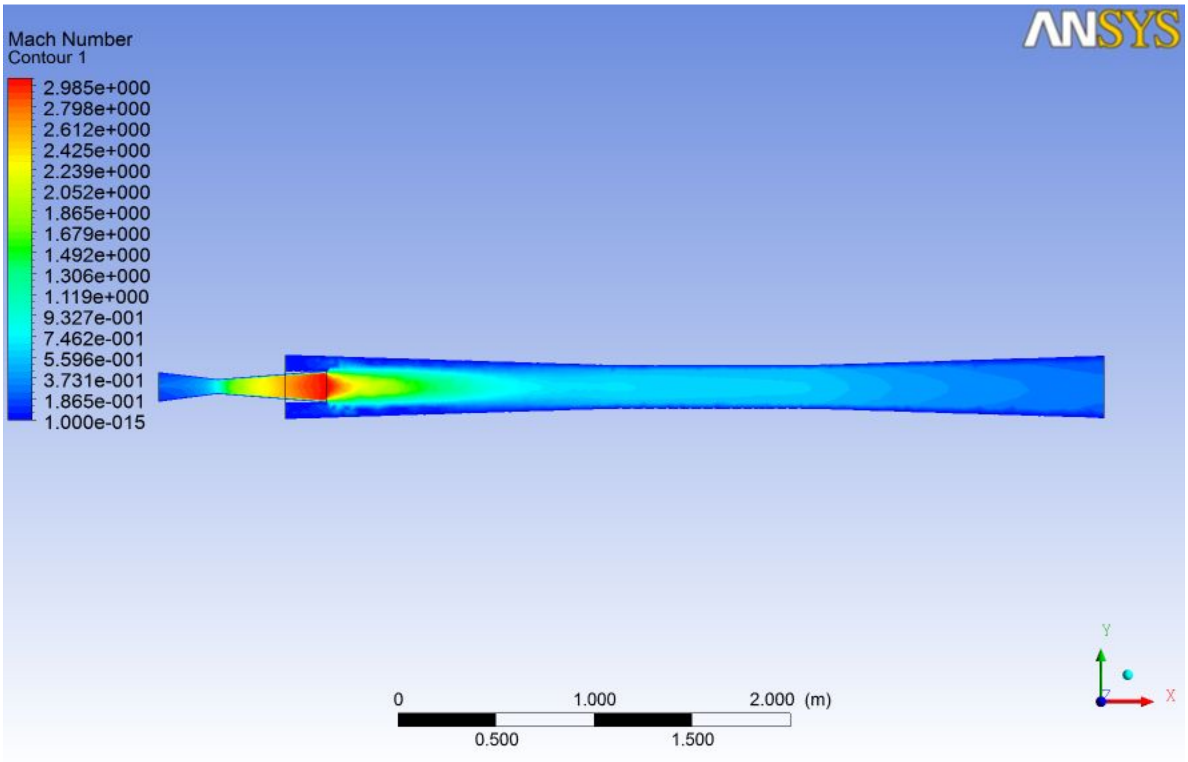

Figure 4.6: Variation of Mach number along longitudinal axis.

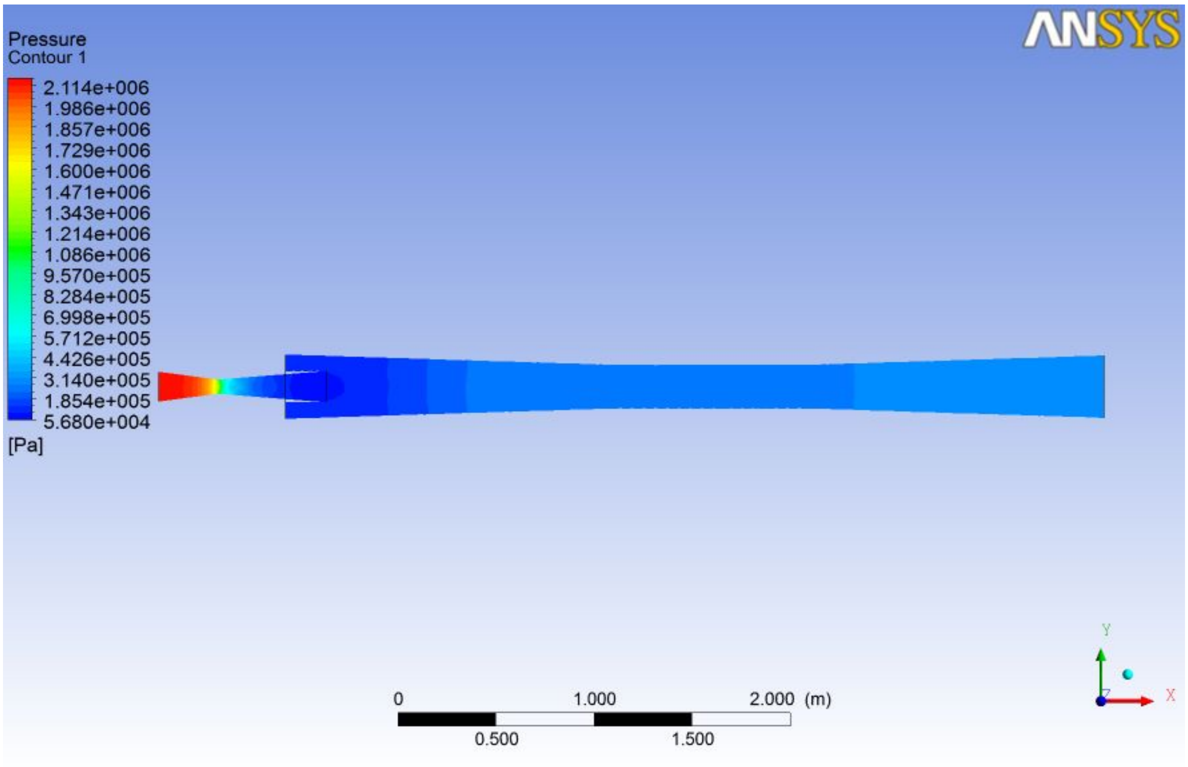

Figure 4.7: Variation of Pressure along longitudinal axis.

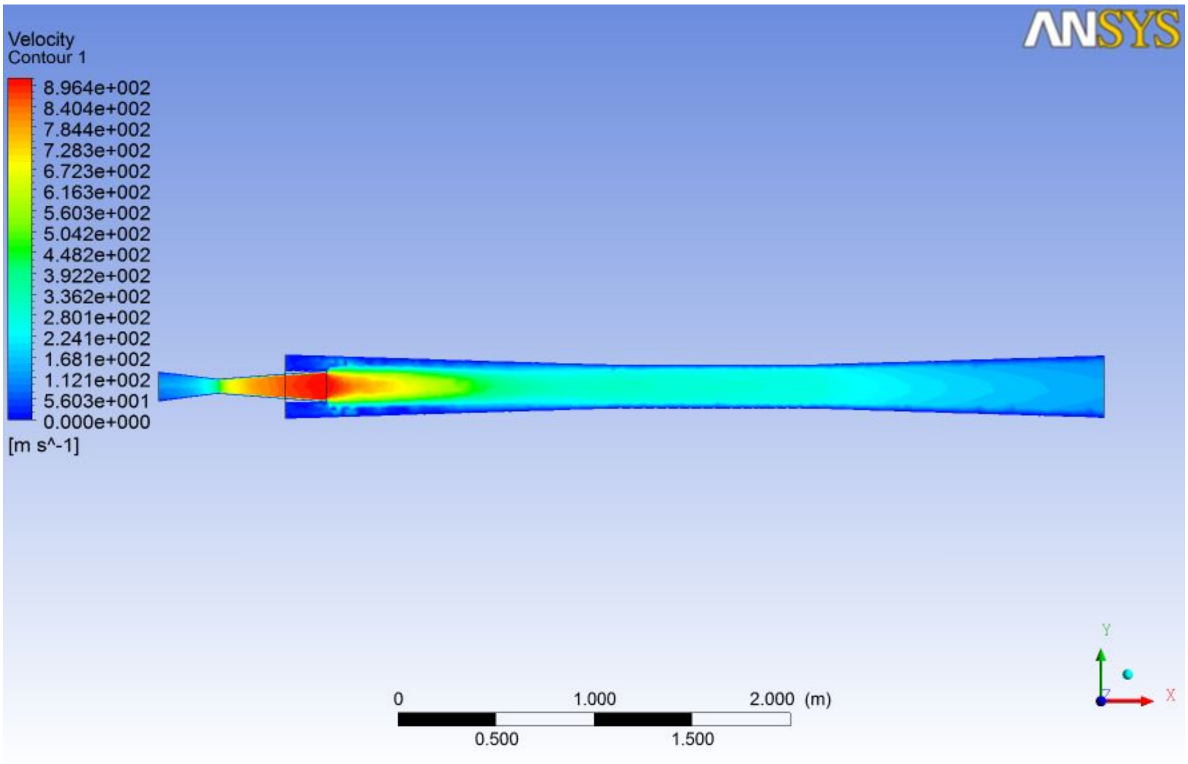

Figure 4.8: Variation of Velocity along longitudinal axis.

4.4.3 Case-3:Secondary inlet pressure=1.47 bar(1.5 kg/cm^2)

Figure 4.9,4.10 and 4.11 represent the variation of mach number contour,pressure contour and velocity contour along the longitudinal axis of thermo-compressor.

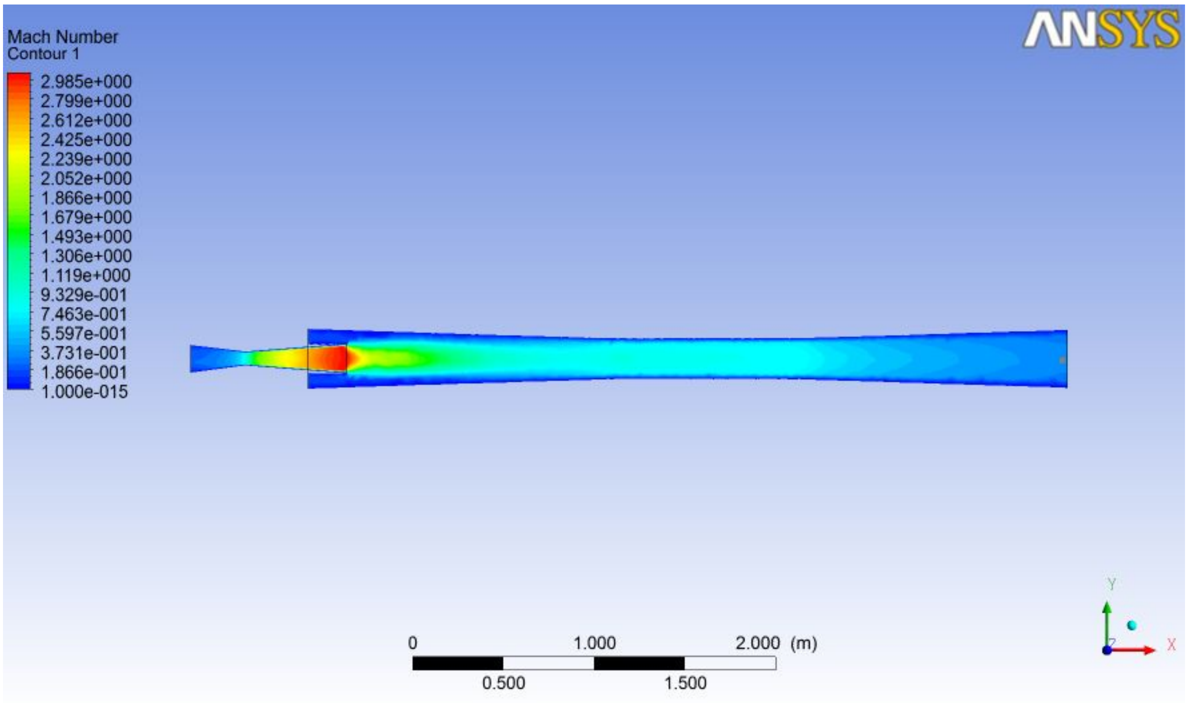

Figure 4.9: Variation of Mach number along longitudinal axis.

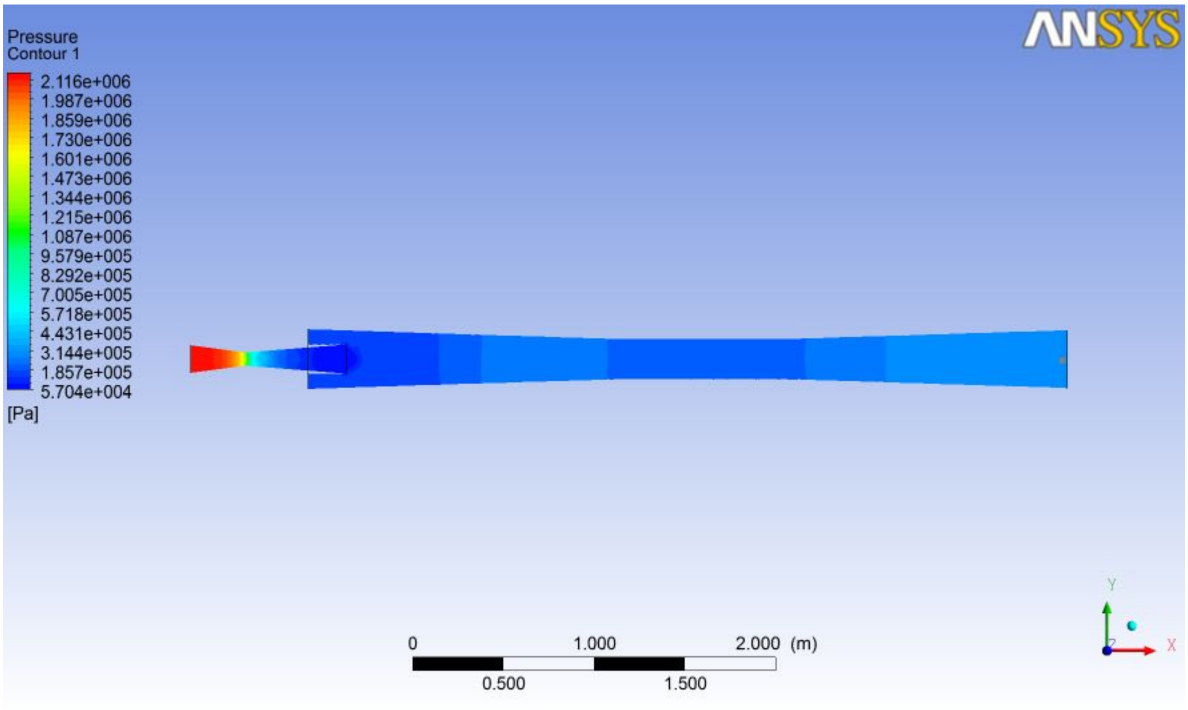

Figure 4.10: Variation of Pressure along longitudinal axis.

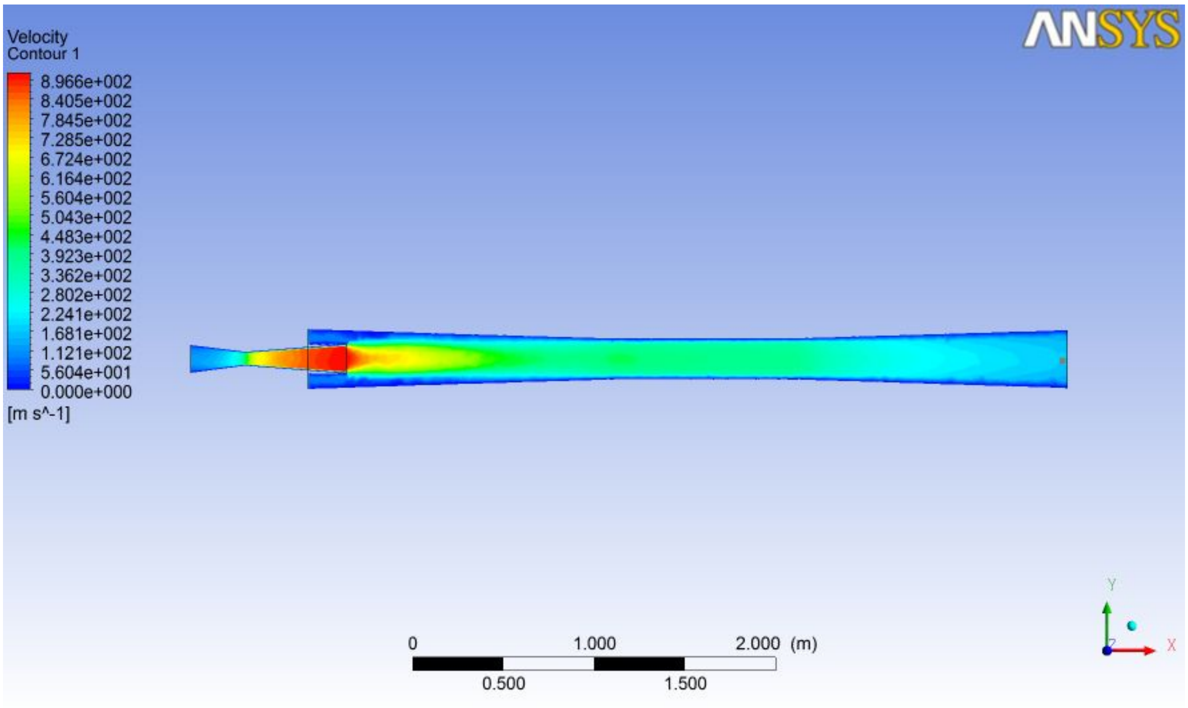

Figure 4.11: Variation of Velocity along longitudinal axis.

4.5 Result and Discussion

CFD Analysis results gives advantage in the study of thermo-compressor because it reveals the phenomena inside the thermo-compressor in detail.Analysis on different range of some important shape parameter and their effect on thermo-compressor has been checked in present study.

The variation of exit pressure,Mach number and velocity of thermo-compressor,with variation in inlet pressure of secondary flow is shown in following figure.chart represents the exit condition between nine different case of secondary flow inlet at 0.3 to 1.7 kg/cm^2 with interval of two.

Fig. 4.12 shows that exit pressure initially increases with increases secondary inlet pressure .However the rate of increases exit pressure is relatively less beyond 0.7 kg/cm^2 secondary inlet pressure.Maximum Exit pressure is reported at 1 kg/cm^2 of secondary inlet pressure which may taken as design consideration.

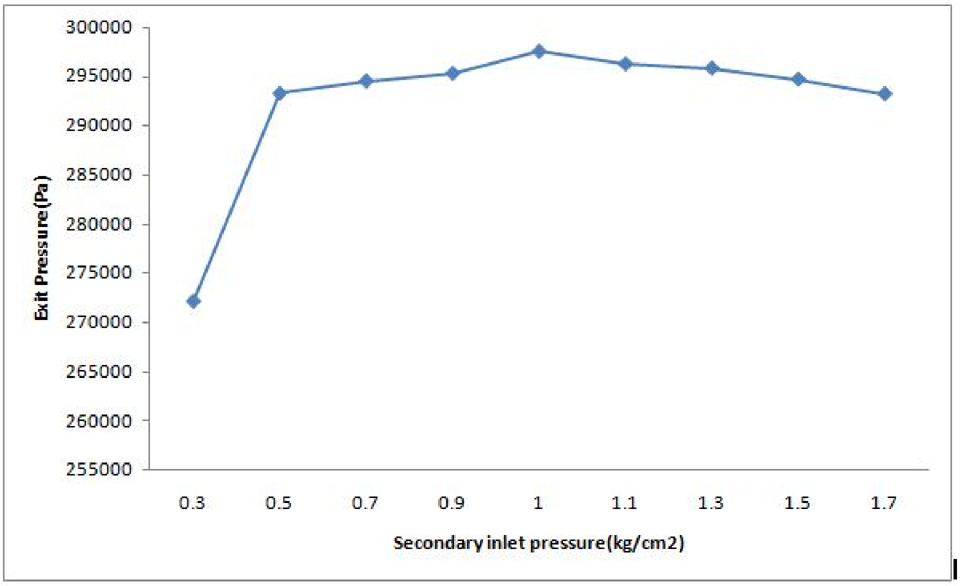

Figure 4.12: Exit Pressure profile.

Fig. 4.13 show the variation of exit velocity with secondary inlet pressure.It is observed that the nature of this variation is opposite to variation of exit pressure as indicated in Fig.5.1.Minimum velocity is observed at 1 kg/cm^2 at secondary inlet pressure.

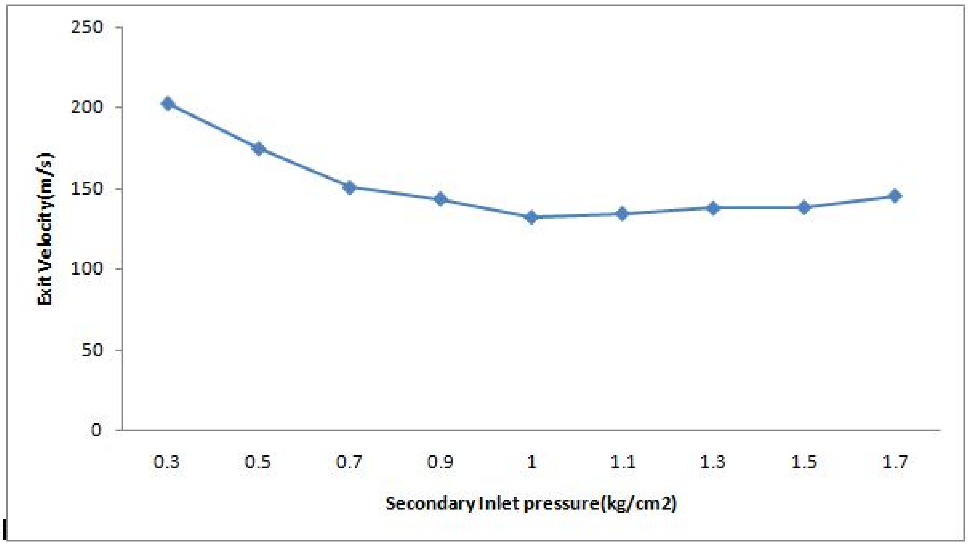

Figure 4.13: Exit velocity profile.

Fig. 4.14 show the variation of exit Mach number with secondary inlet pressure.it interesting to note that exit Mach number for all reported of value of secondary inlet pressure is subsonic which is required of the design of thermo-compressor.

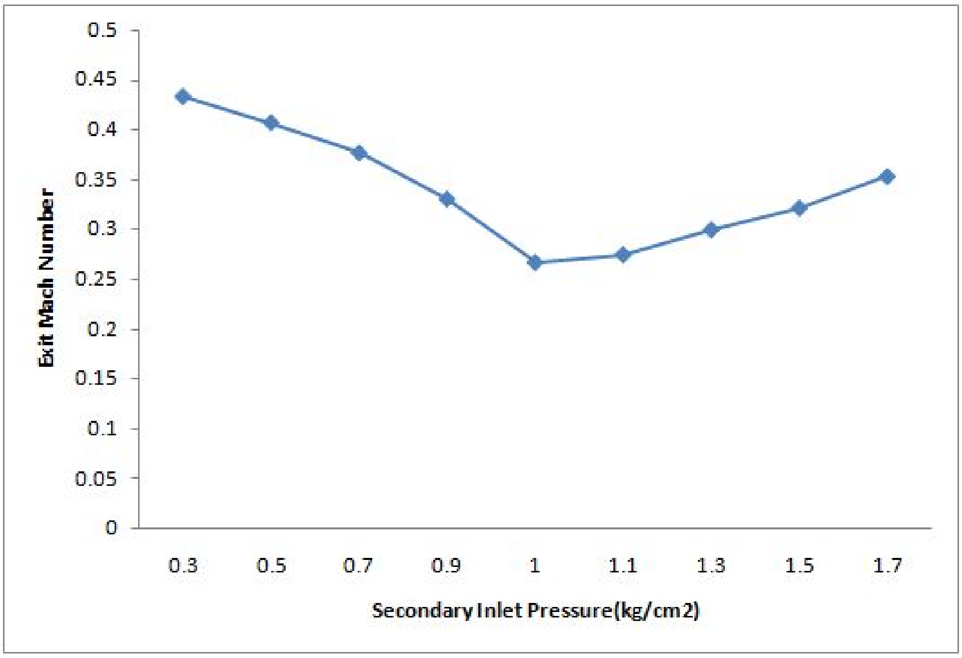

Figure 4.14: Exit Mach number profile.

Chapter 5

Conclusions & Future scope

Conclusions

In the present work of attempt was make to design the thermo-compressor with analytical method and to validated the result obtain with result available in referred literature.Following are major conclusions of present study.

- The results obtain by analytical method are in good agreement with results reported in literature.
- ”C” program for primary or supersonic nozzle is proposed and solid model of thermo-compressor was prepared using output of program.
- CFD analysis was carried out for parametric study of thermo-compressor.Parametric study shows that the 1 kg/cm^2 of secondary inlet pressure is optimum with respect to performance of thermo-compressor.

Future scope

- Same study may be extended with different position of primary or supersonic nozzle.The performance of thermo-compressor may be evaluated at different ER and CR.
- Test setup may be fabricated and result obtained from CFD analysis may be validated by experimental result.

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Appendices

Appendix-1

Method of characteristic

Take Mach number is 3 and γ=1.33,calculate $\nu(M_e)$ from below equation:

$$\nu(M_e) = \sqrt{\frac{\gamma+1}{\gamma-1}} tan^{-1} \sqrt{\frac{\gamma-1}{\gamma+1}} - \tan^{-1}\sqrt{M^2-1}$$

Now calculate,

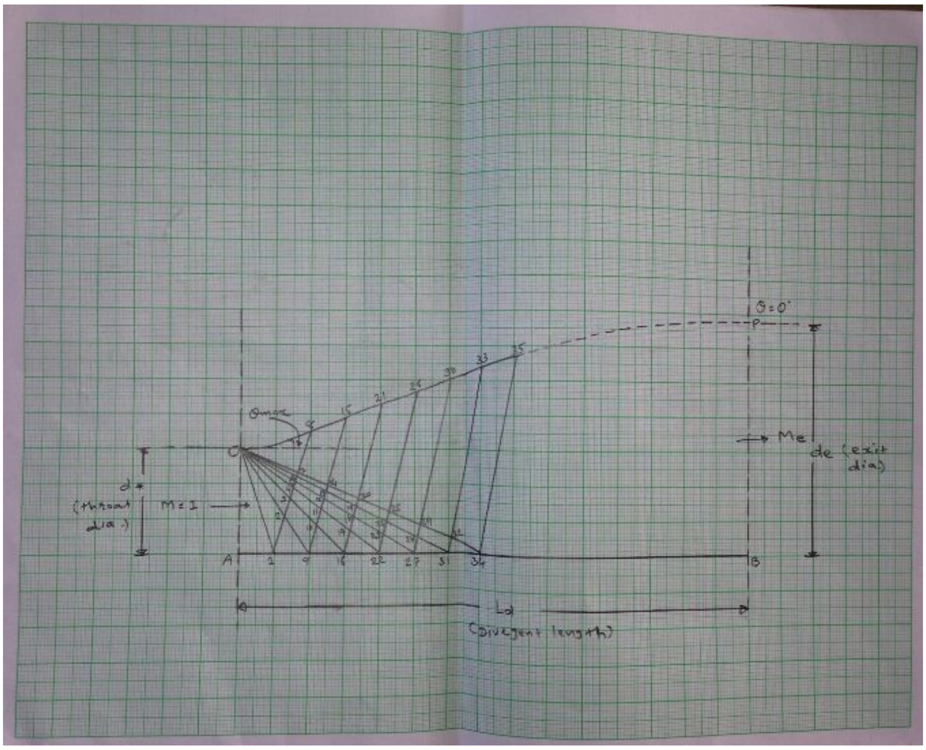
$$\theta_{max} = \frac{\nu(M_e)}{2}$$

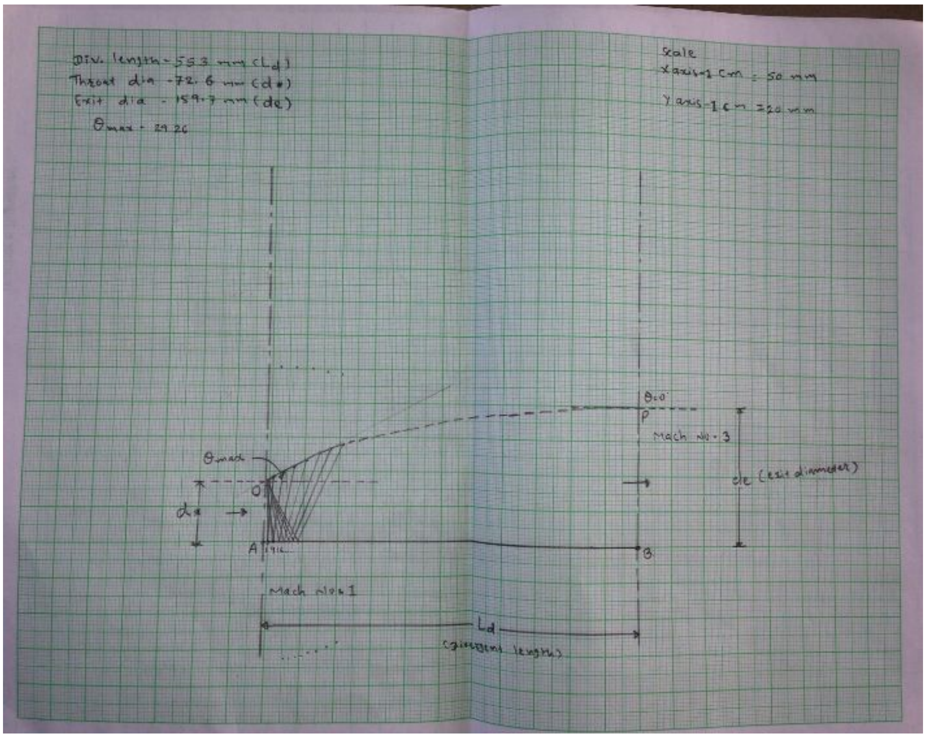
$$\theta_{max} = 29.833$$

Table contain characteristic line and angle of that line which is use to plot the graphical curve.

C^-	θ	
A1	0.833	θ_1
A9	0.833+4	θ_2,θ_9
A16	0.833+8	θ_3,θ_{10},θ_{16}
A22	0.833+12	θ_4,θ_{11},θ_{17},θ_{22}
A27	0.833+16	θ_5,θ_{12},θ_{18},θ_{23},θ_{27}
A31	0.833+20	θ_6,θ_{13},θ_{19},θ_{24},θ_{28},θ_{31}
A34	0.833+24	θ_7,θ_{14},θ_{20},θ_{25},θ_{29},θ_{32},θ_{34}

Below Fig. represent the graphical characteristic curve of supersonic nozzle with the help of the method of characteristic.


θ=0°
P
Me
de (exit dia)
d*
(throat dia.)
M=1
O
A
B
Ld
(Divergent length)


Div. length - 553 mm (Ld)
Throat dia - 72.6 mm (d*)
Exit dia - 159.7 mm (de)
θmax - 29.26
Scale
X axis-1 cm = 50 mm
Y axis-1 cm = 20 mm
θ=0°
P
Mach No. 3
de (exit diameter)
O
d*
A
B
Mach No. 1
Ld
(Divergent length)

Appendix-2

"C++" Program script:

```
#include<iostream.h>
#include<conio.h>
#include<math.h>
#define PI 3.14
void main()
{
clrscr();
float m,P0,Pr,R=461.526,T0,gamma,Di,A1,Ae,De;
float v,rho,alpha,Ar,M=1,lc,Dc,beta,ld,P,Pe;
cout<<"\nEnter m(kg/s):";
cin>>m;
cout<<"\nEnter pressure(bar):";
cin>>P0;
cout<<"\nEnter temperature:";
cin>>T0;
cout<<"\nEnter gamma:";
cin>>gamma;
cout<<"\nEnter inlet diameter(mm):";
cin>>Di;
cout<<"\nEnter convergent angle:";
cin>>alpha;
cout<<"\nEnter area ratio at mach no. 3:";
cin>>Ar;
cout<<"\nEnter divergent angle:";
cin>>beta;
cout<<"\nEnter pressure ratio at mach no. 3:";
cin>>Pr;
alpha=(alpha*PI)/180;
beta=(beta*PI)/180;
A1=(m*sqrt(R*T0))/((P0*pow(10,5))*(M*sqrt(gamma))*pow((1+(((gamma 1)/2)*M*M)),
((gamma+1)/(2*(1-gamma)))));
```

```
Dc=sqrt((4*A1)/PI);
lc=(Di-(Dc*1000))/(2*tan(alpha/2));
Ae=Ar*A1;
De=sqrt((4*Ae)/PI);
ld=((De-Dc)*1000)/(2*tan(beta/2));
P=0.528*P0;
Pe=P0/Pr;
rho=Pe/(R*T);
cout<<"\nArea of throat="<<A1<<" m^2";
cout<<"\nThroat Diameter="<<Dc<<" m";
cout<<"\nConvergent length="<<lc<<" mm";
cout<<"\nExit area="<<Ae<<" m^2";
cout<<"\nExit Diameter="<<De<<" m";
cout<<"\nDivergent length="<<ld<<" mm";
cout<<"\nPressure at throat="<<P<<" bar";
cout<<"\nExit pressure="<<Pe<<" bar";
getch();
}
```

Appendix-3

Gas Properties at $\gamma = 1.33$

M	To/T	Po/p	A/A*
0.02	1.000066	1.00026603	29.1689234
0.04	1.000264	1.00106443	14.59465812
0.06	1.000594	1.00239616	9.741109004
0.08	1.001056	1.00426281	7.317747449
0.1	1.00165	1.00666664	5.866470471
0.12	1.002376	1.00961053	4.901246031
0.14	1.003234	1.01309801	4.213776652
0.16	1.004224	1.01713327	3.699915331
0.18	1.005346	1.02172115	3.301804171
0.2	1.0066	1.02686719	2.98472984
0.22	1.007986	1.03257756	2.726603326
0.24	1.009504	1.03885913	2.512699812
0.26	1.011154	1.04571947	2.332826307
0.28	1.012936	1.05316684	2.179703146
0.3	1.01485	1.06121021	2.047992894
0.32	1.016896	1.06985928	1.933693413
0.34	1.019074	1.07912448	1.833745135
0.36	1.021384	1.08901699	1.745769251
0.38	1.023826	1.09954878	1.66788858
0.4	1.0264	1.11073256	1.598602167
0.42	1.029106	1.12258186	1.536695725
0.44	1.031944	1.13511103	1.48117649
0.46	1.034914	1.14833524	1.43122508
0.48	1.038016	1.16227052	1.386159386
0.5	1.04125	1.17693378	1.345407129
0.52	1.044616	1.19234281	1.308484754
0.54	1.048114	1.20851634	1.274981008
0.56	1.051744	1.22547403	1.244544051
0.58	1.055506	1.24323651	1.216871214
0.6	1.0594	1.2618254	1.191700828

0.62	1.063426	1.28126336	1.168805618
0.64	1.067584	1.30157408	1.147987343
0.66	1.071874	1.32278235	1.129072416
0.68	1.076296	1.34491405	1.111908283
0.7	1.08085	1.36799623	1.096360442
0.72	1.085536	1.3920571	1.082309941
0.74	1.090354	1.41712609	1.069651298
0.76	1.095304	1.44323388	1.058290736
0.78	1.100386	1.47041243	1.048144703
0.8	1.1056	1.49869504	1.039138603
0.82	1.110946	1.52811638	1.031205723
0.84	1.116424	1.55871252	1.024286303
0.86	1.122034	1.59052098	1.018326747
0.88	1.127776	1.62358078	1.013278938
0.9	1.13365	1.65793251	1.009099639
0.92	1.139656	1.69361831	1.005749981
0.94	1.145794	1.73068201	1.003195014
0.96	1.152064	1.76916912	1.001403312
0.98	1.158466	1.80912687	1.000346628
1	1.165	1.85060434	0.999999594
1.02	1.171666	1.89365244	1.000339453
1.04	1.178464	1.93832403	1.001345822
1.06	1.185394	1.98467391	1.003000487
1.08	1.192456	2.03275897	1.005287214
1.1	1.19965	2.08263817	1.008191589
1.12	1.206976	2.13437267	1.011700868
1.14	1.214434	2.18802587	1.015803848
1.16	1.222024	2.24366348	1.02049075
1.18	1.229746	2.30135359	1.025753117
1.2	1.2376	2.36116678	1.031583717
1.22	1.245586	2.42317613	1.03797646

1.24	1.253704	2.48745739	1.044926323
1.26	1.261954	2.55408896	1.052429285
1.28	1.270336	2.62315207	1.060482259
1.3	1.27885	2.6947308	1.069083043
1.32	1.287496	2.76891219	1.078230269
1.34	1.296274	2.84578635	1.087923357
1.36	1.305184	2.92544654	1.098162473
1.38	1.314226	3.00798924	1.108948496
1.4	1.3234	3.0935143	1.120282982
1.42	1.332706	3.18212501	1.132168137
1.44	1.342144	3.27392822	1.144606786
1.46	1.351714	3.36903444	1.157602352
1.48	1.361416	3.46755794	1.171158832
1.5	1.37125	3.56961689	1.185280777
1.52	1.381216	3.67533347	1.199973275
1.54	1.391314	3.78483397	1.215241935
1.56	1.401544	3.89824895	1.231092871
1.58	1.411906	4.01571331	1.247532688
1.6	1.4224	4.13736649	1.264568475
1.62	1.433026	4.26335255	1.282207789
1.64	1.443784	4.39382034	1.300458649
1.66	1.454674	4.5289236	1.319329525
1.68	1.465696	4.66882116	1.338829334
1.7	1.47685	4.81367705	1.35896743
1.72	1.488136	4.96366064	1.379753602
1.74	1.499554	5.11894683	1.401198065
1.76	1.511104	5.27971619	1.423311459
1.78	1.522786	5.44615513	1.446104845
1.8	1.5346	5.61845605	1.469589701
1.82	1.546546	5.79681754	1.493777919
1.84	1.558624	5.98144452	1.518681806

1.86	1.570834	6.17254845	1.54431408
1.88	1.583176	6.3703475	1.570687871
1.9	1.59565	6.57506674	1.597816717
1.92	1.608256	6.78693832	1.62571457
1.94	1.620994	7.00620169	1.654395791
1.96	1.633864	7.23310378	1.683875152
1.98	1.646866	7.46789924	1.714167838
2	1.66	7.71085058	1.745289448
2.02	1.673266	7.96222848	1.777255996
2.04	1.686664	8.22231194	1.810083914
2.06	1.700194	8.49138852	1.843790053
2.08	1.713856	8.7697546	1.878391684
2.1	1.72765	9.05771559	1.913906505
2.12	1.741576	9.35558617	1.95035264
2.14	1.755634	9.66369055	1.987748642
2.16	1.769824	9.98236271	2.0261135
2.18	1.784146	10.3119467	2.065466639
2.2	1.7986	10.6527967	2.105827922
2.22	1.813186	11.0052777	2.14721766
2.24	1.827904	11.3697655	2.18965661
2.26	1.842754	11.7466467	2.233165983
2.28	1.857736	12.1363198	2.277767445
2.3	1.87285	12.5391945	2.323483124
2.32	1.888096	12.9556929	2.370335614
2.34	1.903474	13.3862493	2.41834798
2.36	1.918984	13.8313103	2.467543759
2.38	1.934626	14.291336	2.517946973
2.4	1.9504	14.7667993	2.569582125
2.42	1.966306	15.2581868	2.622474211
2.44	1.982344	15.7659991	2.676648723
2.46	1.998514	16.2907512	2.732131652

2.48	2.014816	16.8329723	2.788949499
2.5	2.03125	17.3932071	2.847129274
2.52	2.047816	17.9720152	2.906698508
2.54	2.064514	18.5699722	2.967685256
2.56	2.081344	19.1876698	3.0301181
2.58	2.098306	19.825716	3.094026163
2.6	2.1154	20.4847359	3.159439105
2.62	2.132626	21.1653717	3.226387139
2.64	2.149984	21.8682836	3.29490103
2.66	2.167474	22.5941495	3.365012105
2.68	2.185096	23.3436661	3.436752259
2.7	2.20285	24.1175493	3.510153962
2.72	2.220736	24.9165339	3.585250264
2.74	2.238754	25.7413751	3.662074803
2.76	2.256904	26.5928481	3.740661811
2.78	2.275186	27.471749	3.821046123
2.8	2.2936	28.3788954	3.903263181
2.82	2.312146	29.3151264	3.987349043
2.84	2.330824	30.2813034	4.073340391
2.86	2.349634	31.2783108	4.161274535
2.88	2.368576	32.3070562	4.251189424
2.9	2.38765	33.3684708	4.343123651
2.92	2.406856	34.4635105	4.43711646
2.94	2.426194	35.5931558	4.533207755
2.96	2.445664	36.7584129	4.631438109
2.98	2.465266	37.9603137	4.731848767
3	2.485	39.199917	4.834481659