

**International Institute for Aerospace Engineering and Management**

Jain Global Campus, Kanakapura Taluk - 562112,

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**A Project Report On**

**DESIGN OF TRUNCATED IDEAL CONTOUR NOZZLE**

**Submitted in partial fulfilment for the award of the degree of**

**BACHELOR OF TECHNOLOGY**

**IN**

**AEROSPACE ENGINEERING**

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**CERTIFICATE**

This is to certify that the project work titled, **Design of Truncated Ideal Contour Nozzle**, is carried out by **Anupama S Dixit (14BT1AE010), Deepti S D (14BT1AE018) and Ibtesam Shaikh (14BT1AE090)**, bonafide students of Bachelor of Engineering at the IIAEM, Jain University, in partial fulfilment for the award of **Bachelor of Technology in Aerospace Engineering**, during the year **2014-2018.**

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**DECLARATION**

We**, Anupama S Dixit (14BT1AE010), Deepti S D (14BT1AE018) and Ibtesam Shaikh (14BT1AE090),** students of eighth semester B.Tech in **Aerospace Engineering** at **IIAEM, Jain University**, hereby declare that the dissertation titled **“Design of Truncated Ideal Contour Nozzle”** has been carried out by us and submitted in partial fulfilment for the award of **Bachelor of Technology in Aerospace Engineering,** during the academic year **2014-2018.** Further, the matter embodied in the dissertation has not been submitted by anybody for the award of any degree or diploma to any university, to the best of our knowledge and faith.

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# ABSTRACT

The aim of the project was to design a Truncated Ideal Contour nozzle for specified design parameters. An ideal contour nozzle was designed using the Method of Characteristics and truncated to 80% of its length to improve the performance.

The Method of Characteristics was applied to determine the flow properties and co-ordinates of the ideal contour nozzle. A program was written in C to determine the points and flow properties of all the grid points. From trigonometry and graph, the co-ordinates of the grid points were determined.

Using these coordinates an Ideal Contour Nozzle was designed and truncated in modelling software.

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# NOMENCLATURE AND ABBREVIATIONS

|  |  |
| --- | --- |
| MoC | Method of Characteristics |
| TIC | Truncated Ideal Contour |
|  | Deflection angle |
|  | Prandtl Meyer angle |
| M | Mach number |
|  | Mach angle |

# CHAPTER 1

# INTRODUCTION

## Objective

To design a Truncated Ideal Contour nozzle (TIC) using the Method of Characteristics (MoC).

The project work was initiated with an objective of designing a dual bell nozzle. Due to complexity of the problem and time constraint, the objective was reduced to designing of a Truncated Ideal Contour nozzle (TIC) which is the first stage of designing a dual bell nozzle.

## 1.2 Rocket nozzles

A rocket engine nozzle is a propelling nozzle (usually of the de Laval type) used in a rocket engine to expand and accelerate the hot gases from combustion so as to produce thrust according to Newton’s laws of motion. Combustion gases are produced by burning the propellants in combustor, and they exit the nozzle at a very high speed (hypersonic).

The rocket’s efficiency is primarily dependent upon the nozzle’s ability to convert the thermal energy of the fuel to kinetic energy. The main nozzle wall contour plays a critical role in this conversion. It is also important to ensure shocks do not occur within the nozzle. Shocks in the nozzle will disrupt the supersonic flow and will create large losses during the conversion of thermal energy to kinetic energy. The wall contour of the nozzle is the defining factor in whether shocks will or will not form within the nozzle.

It has been found that for maximum thrust, the flow direction of the fluid under sonic conditions should be offset from the axis-symmetric line by an angle equal to 𝜈exit the Prandtl- Meyer expansion angle associated with the desired exit Mach number of the nozzle.

Traditionally, the supersonic nozzle is divided in two parts. The supersonic portion is independent of the upstream conditions of the sonic line. We can study the subsonic portion independently. The latter is used to give a sonic flow at the throat. We design a type of nozzle giving a parallel and uniform flow at the exit section. It is named by Minimum Length Nozzle with centered expansion, which gives the minimal length compared to the other existing types.

Supersonic nozzles can be divided into two different types: gradual-expansion nozzles and minimum-length nozzles.

Gradual-expansion nozzles are typically used in applications where maintaining a high-quality flow at the desired exit conditions is of importance (e.g., supersonic wind tunnels). For other types of applications (e.g., rocket nozzles), the large weight and length penalties associated with gradual expansion nozzles make them unrealistic; therefore minimum-length nozzles, which utilize a sharp corner to provide the initial expansion, are commonly used.

For both gradual-expansion and minimum-length nozzles, the flow can be divided into simple and nonsimple regions. A non-simple region is characterized by Mach wave reflections and intersections. In order to meet the requirement of uniform conditions at the nozzle exit, it is desirable to minimize the non-simple region as much as possible. This can be performed by designing the nozzle surface such that Mach waves (e.g., characteristics) are not produced or reflected while the flow is straightened. The Method of Characteristics is therefore applied to allow the design of a supersonic nozzle which meets these requirements.

In order to expand an internal steady flow through a duct from subsonic to supersonic speed the duct has to be convergent - divergent in shape. If the nozzle contour is not proper, shock waves may occur inside the duct. The Method of Characteristics provides a technique for properly designing the contour of a supersonic nozzle for shock free, isentropic flow, taking into account the multidimensional flow inside the duct.

Rocket nozzles are short in order to minimize weight. Also, in cases where rapid expansions are desirable, such as the non-equilibrium flow in modern gas dynamic lasers, the nozzle length is as short as possible In such minimum- length nozzles, the expansion section is shrunk to a point, and the expansion takes place through a centered Prandtl-Meyer wave emanating from a sharp-corner throat with an angle 𝜃𝑊𝑚𝑎 ,𝑀𝐿 as sketched in Fig.1.1. The length of the supersonic nozzle, denoted as L in Fig 1.1 is the minimum value consistent with shock free, isentropic flow. If the contour is made shorter than L, shocks will develop inside the nozzle.

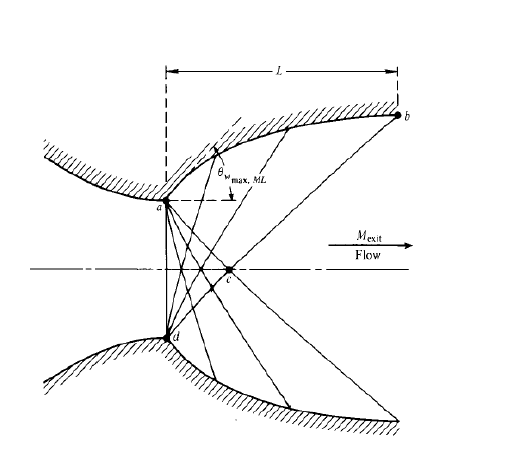


Fig 1.1: Minimum length Supersonic Nozzle Design

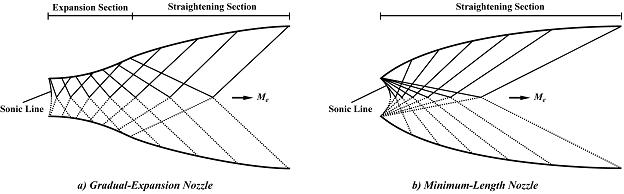


Fig 1.2: Types of supersonic nozzles

Generally, the 3 primary groups of nozzle types include:

1. Cone (conical, linear)
2. Bell (contoured, shaped, classic converging-diverging)
3. Annular (spike, aerospike, plug, expansion, expansion-deflection)

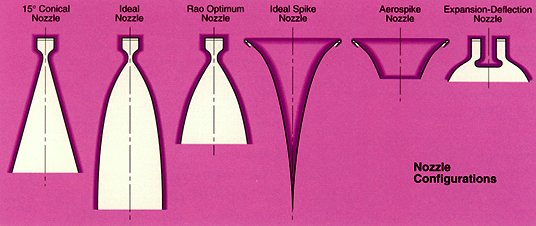


Fig 1.3: Primary types of nozzles

# CHAPTER 2

# LITERATURE SURVEY

1. **Critical Assessment of Dual Bell Nozzles**  
   M. Frey and G. Hagemann, Jn. Of Propulsion and Power, Vol. 15, No.1, 1999

This paper provides the behaviour of wall pressure profile at the point of inflection in the DB nozzle at different altitudes.

Creation of side loads during the transition phase of constant pressure extensions is analysed in brief. It also explains the variation of performance parameters at different pressure conditions (such as at vacuum and sea level).

The shortened duration of flow separation can be achieved by controlling the engine throttle and variation of chamber pressure. This is provided as the conclusion.

1. **Cold flow testing of Dual bell nozzles in altitude simulation chamber**

EUCASS, R. Stark, Ch. Böhm, O. J. Haidn, H. Zimmermann, German Aerospace Centre (DLR).

This deals with testing of DB nozzle which was designed using the Method of Characteristics. DLR’s cold gas subscale test facility P6.2, located at Lampoldshausen test site in Germany, is briefly explained. Performance parameters of DB nozzle in altitude simulation chamber have been studied.

One focus of feature DB nozzle tests will be on the influence of total and back pressure fluctuations during transition regime. The present tests demonstrated that the applied P6.2 modifications exclude undesired flip flops.

1. **Flow separation in Rocket nozzles under high altitude condition**

R. Stark, C.Genin, Springer-Verlag Berlin Heidelberg 2016

The knowledge of flow separation in rocket nozzles is crucial for rocket engine design and optimum performance. But typically flow separation is studied under sea level conditions disregarding the ambient flow properties. An experiment was conducted to study the influence of altitude and thus the ambient flow properties on flow separation. And from the experimental results, it was observed that as the altitude increases the point of flow separation moves up stream.

1. **Experimental and Numerical study of Dual bell Nozzle flow**  
    C.Genin, R.Stark, O.Haidin,K.Quering and M.frey, Jn. of Space Propulsion and Space Transportation

The dual bell nozzle has been tested in hot flow. The observation of shock system in the contour inflection gives information on the position and the shape of the separation front. It is observed that, at sea level the results are satisfactory but at the higher altitudes the NPR value increases and thus flow separation is significant.

1. **Numerical solution for design of a traditional aerospike nozzle using the Method of Characteristics**

Ayub Padania, Sanjay Kumar Sardiwal, D. Harika Chowdary, M.V. Sai Sharath, Sushma Artham

A computer code is developed which uses the Method of Characteristics and stream functions to define the traditional aerospike nozzle contour for inviscid, irrotational supersonic flows of any working fluid for any user defined exit mach number.

1. **Design of a supersonic nozzle using the Method of Characteristics**

Md Akhtar Khan, Sanjay Kumar Sardiwal, M.V.Sai Sharath, D.Harika Chowdary

A method based on the theory of characteristics is presented for two-dimensional, supersonic nozzle design.

Minimum length of the supersonic nozzle is calculated for the optimum Mach number at the nozzle exit with uniform flow at the diverging section of the nozzle by developing a MATLAB program. Numerical solution is established for the two dimensional, steady, inviscid, irrotational and supersonic flow.

1. **Turbulence modelling for predicting flow separation in rocket nozzles**

Allamaprabhu Yaravintelimath

Convergent-Divergent (C-D) nozzles are used in rocket engines to produce thrust as a reaction to the acceleration of hot combustion chamber gases in the opposite direction. To maximize the engine performance at high altitudes, large area ratio, bell-shaped or contoured nozzles are used.

The specifications for the contour nozzle designed in this project were taken from this paper.

# CHAPTER 3

# METHOD OF CHARACTERISTICS

## 3.1 Definition

In [mathematics](https://en.wikipedia.org/wiki/Mathematics), the Method of Characteristics is a technique for solving [partial differential equations](https://en.wikipedia.org/wiki/Partial_differential_equations). Typically, it applies to [first-order equations](https://en.wikipedia.org/wiki/First-order_partial_differential_equation), although more generally the Method of Characteristics is valid for any [hyperbolic partial differential equation](https://en.wikipedia.org/wiki/Hyperbolic_partial_differential_equation).

The MoCis a very convenient tool to calculate isentropic portions within a supersonic flow. This is a numerical method, but the merit is that the method itself determines the grid (or mesh) it requires. Other CFD methods can be used for the same purpose but these require more extensive numerical calculations.

Characteristic lines are curves in the flow where the velocity is continuous but the first derivative of velocity is discontinuous.

## 3.2 Theory of the Method of Characteristics

Governing Equations for a two-dimensional compressible, irrotational flow can be written as

The above equation is a statement that the flow is irrotational. These governing equations form a non-linear set of Partial Differential Equations. The solutions can be classified as follows,

Elliptic, if (u2+ v2)/a2< 1

Parabolic, if (u2+ v2)/a2= 1

Hyperbolic, if **(u2+ v2)/a2> 1**.

Supersonic flows withM >1, belong to the Hyperbolic class. One of the properties of Hyperbolic Equations is the existence of characteristic lines or directions. In a supersonic flow at every point there can exists small disturbance waves called Mach Waves. These are, in fact, the characteristic lines.

The Direction of Mach Waves is the characteristic direction. Across a characteristic line, velocity derivatives may be discontinuous, but velocity itself will be discontinuous. Along the characteristic lines, the Compatibility Relations hold good.

## 3.3 Compatibility relations

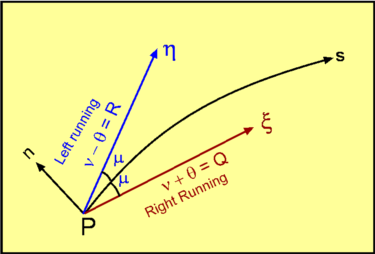


Fig 3.1: Left and right running characteristic lines

Consider a stream line in a supersonic flow as in figure 3.1. The coordinate **s** axis is aligned along the streamline and the other axis n, normal to it. There are two Mach lines at a point P. The one to the left of the streamline is a η characteristic and the one to the right is called ξ characteristic. Note that each of these is inclined at an angle **μ** to the streamline. It can be shown that along η characteristic,

i.e., , where R is a constant.

Similarly along a **ξ** characteristic,

i.e., , where Q is a constant.

The above equations are the Compatibility Relations. Essentially, they say that Q and R are invariant in ξ and η directions respectively. These are known as Riemann Invariants and are relatively simple because of the application they are being applied to here.

## 3.4 Computing with the Method of Characteristics

Using the Method of Characteristics, ν and θ at a particular point can be computed.Once these two variables are determined at any point in the flow, other quantities of interest such as Mach number, flow velocity and pressure can be determined using isentropic relations.

Consider a curve AB in the flow along which ν and θ are known. This curve is known as a starting curve. The procedure to calculate values at point C are shown in below figure.

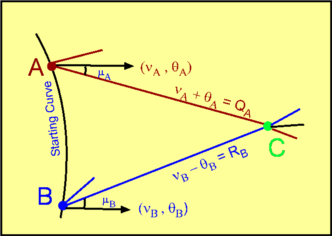


Fig 3.2: Computing using MOC

Now,

νC – θC = νA-θA = QA

and

νC – θC = νB - θB = RB

Solving for νC and θC,

Or,

Once the flow at C is calculated, it is possible to continue and calculate the flow downstream.

In practice, to gain accuracy, a number of points on the starting curve are considered. Mach Lines are drawn from each of them. Then the procedure marches downstream calculating the flow at every subsequent point. In this process, a net or a grid of points is created as shown in the figure below.

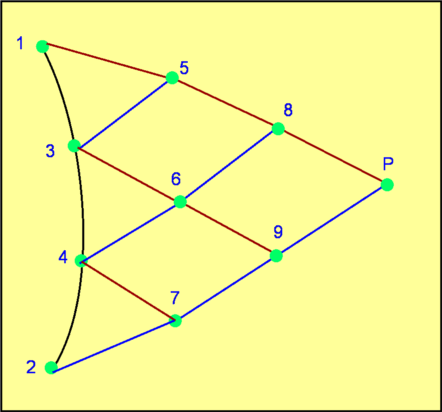


Fig 3.3: Grid points

# CHAPTER 4

# NOZZLE SPECIFICATIONS

The data given in table 4.1 are the nozzle specifications of a reference nozzle [11].

**Table 4.1: Reference nozzle specifications**

|  |  |
| --- | --- |
| Area Ratio | 13.77 |
| Nozzle Length | 300mm |
| Throat Radius | 33.54mm |
| Throat upstream wall radius | 5.5 |
| Throat downstream wall radius | 0.5 |
| Throat wall angle | 34.77 |
| Nozzle exit angle | 10 |
| Design Mach number | 4.3 |
| Feeding gas | Air |

# CHAPTER 5

# CONTOUR DESIGN USING MoC

## 5.1 C-programming to determine flow properties

**Objective of the program**: To find the flow properties at all the grid points which include axis line points, points on the first and the last characteristic line, the wall points and the remaining interior points.

**Validation of the program**: The program gives flow properties at all the grid points for various nozzle specifications and flow parameters. The results of this program were validated with the following problem statement:

Compute and graph the contour of a two-dimensional minimum-length nozzle for the expansion of air to a design exit Mach number of 2.4. [1]

**Program:**

*#include<stdio.h>*

*#include<math.h>*

*void main()*

*{*

*float m, nu, theta[500], Nu[500], MinusK[500], PlusK[500], z[500], thetamax, t, a, rem=0.0, remain[2];*

*int n, dt = 0, i, p, j=0, jo ,l=0 , k=2, pts[200], total=0, points[200], pnts[200], wallpts[200], intpts[200], y[200], first = 0, second = 1, x=2, q=1;*

*printf("Enter the Design Exit Mach Number.\n");*

*scanf("%f",&m);*

*printf("Enter the Flow Deflection Angle.\n");*

*scanf("%f",&t);*

*printf("Enter the Number of Characteristics to be considered.\n");*

*scanf("%d",&n);*

*rem = fmod(t,(n-1));*

*printf("\nRem=%f\n",rem);*

*a=t-rem;*

*remain[0] = rem;*

*printf("\nThe value of a=%f",a);*

*dt = a/(n-1);*

*printf("\nDelta Theta = %d\n\n", dt);*

*theta[pts[0]] = rem;*

*printf("\nThe points on the First Left Running Characteristic line are as follows:\n\n");*

*for(i=0;i<n;i++)*

*{*

*pts[i]= ++l;*

*//printf("%d\n",pts[i]);*

*printf("Pts[%d] = %d\n", i , pts[i]);*

*}*

*printf("\n Flow properties of the points on the First Left Running Characteristic line:\n\n");*

*for(i=0; i<n; i++)*

*{*

*theta[pts[i]] = rem + (dt\*j);*

*Nu[pts[i]] = theta[pts[i]];*

*MinusK[pts[i]] = theta[pts[i]]+ Nu[pts[i]];*

*PlusK[pts[i]] = theta[pts[i]] - Nu[pts[i]];*

*j=j+1;*

*printf("Point %d\tMinusK[%d] = %f\tPlusK[%d] = %f\tTheta[%d] = %f\tNu[%d] = %f\n", pts[i], pts[i], MinusK[pts[i]], pts[i], PlusK[pts[i]], pts[i], theta[pts[i]], pts[i], Nu[pts[i]]);*

*}*

*points[0] = 1;*

*z[0]= n+1;*

*printf("\nThe points on the Axis line are as follows:\n\n");*

*printf("Points[0] = %d\n",points[0]);*

*for(i=0;i<n-1;i++)*

*{*

*points[i+1]= points[i] + z[i];*

*printf("Points[%d] = %d\n",(i+1),points[i+1]);*

*z[i+1]=z[i]-1;*

*}*

*MinusK[points[0]] = MinusK[pts[0]];*

*PlusK[points[0]] = PlusK[pts[0]];*

*theta[points[0]] = theta[pts[0]];*

*Nu[points[0]] = Nu[pts[0]];*

*printf("\n Flow properties of the points on the Axis line: \n");*

*printf("\nMinusK[%d] = %f\tPlusK[%d] = %f\tTheta[%d] = %f\tNu[%d] = %f\n", points[0] , MinusK[points[0]], points[0] , PlusK[points[0]], points[0] , theta[points[0]], points[0] , Nu[points[0]]);*

*for (i=1; i<n; i++)*

*{*

*theta[points[i]]=0;*

*Nu[points[i]]= Nu[pts[i]]+theta[pts[i]];*

*MinusK[points[i]]= theta[points[i]] + Nu[points[i]];*

*PlusK[points[i]]= theta[points[i]] - Nu[points[i]];*

*printf("MinusK[%d] = %f\tPlusK[%d] = %f\tTheta[%d] = %f\tNu[%d] = %f\n",points[i], MinusK[points[i]],points[i], PlusK[points[i]],points[i], theta[points[i]],points[i],Nu[points[i]]);*

*}*

*pnts[0]= n;*

*y[0]=n;*

*printf("\n\nThe points on the Last Right Running Characteristic line:\n\n");*

*printf("Pnts[0] = %d\n",pnts[0]);*

*for(i=0;i<n-1;i++)*

*{*

*pnts[i+1]= pnts[i] + y[i];*

*printf("Pnts[%d] = %d\n",(i+1),pnts[i+1]);*

*y[i+1]=y[i]-1;*

*}*

*printf("\n Flow properties of the points on the Last Right Running Characteristic line:\n");*

*theta[pnts[0]] = t;*

*Nu[pnts[0]] = t;*

*MinusK[pnts[0]] = theta[pnts[0]] + Nu[pnts[0]];*

*PlusK[pnts[0]] = theta[pnts[0]] - Nu[pnts[0]];*

*printf("\nMinusK[ %d] = %f\tPlusK[ %d] = %f\tTheta[ %d] = %f\tNu[ %d] = %f\n",pnts[0], MinusK[pnts[0]],pnts[0], PlusK[pnts[0]],pnts[0], theta[pnts[0]],pnts[0], Nu[pnts[0]]);*

*for (i=1; i<n;i++)*

*{*

*theta[pnts[i]]= dt\*(n-k);*

*Nu[pnts[i]] = - theta[points[i]] + Nu[points[i]] + theta[pnts[i]];*

*MinusK[pnts[i]]= theta[pnts[i]] + Nu[pnts[i]];*

*PlusK[pnts[i]]= theta[pnts[i]] - Nu[pnts[i]];*

*printf("MinusK[%d] = %f\tPlusK[%d] = %f\tTheta[%d] = %f\tNu[%d] = %f\n",pnts[i], MinusK[pnts[i]],pnts[i], PlusK[pnts[i]], pnts[i],theta[pnts[i]], pnts[i],Nu[pnts[i]]);*

*k++;*

*}*

*wallpts[0] = n+1;*

*y[0] = n;*

*printf("\n\nThe points on the Nozzle Wall:\n\n");*

*printf("WallPts[0] = %d\n",wallpts[0]);*

*for(i=0;i<n-1;i++)*

*{*

*wallpts[i+1] = wallpts[i] + y[i];*

*printf("WallPts[%d] = %d\n",(i+1),wallpts[i+1]);*

*y[i+1] = y[i] - 1;*

*}*

*printf("\nFlow properties of the points on the Nozzle Wall: \n\n");*

*for (i=0; i<n; i++)*

*{*

*theta[wallpts[i]] = theta[pnts[i]];*

*Nu[wallpts[i]] = Nu[pnts[i]];*

*MinusK[wallpts[i]] = MinusK[pnts[i]];*

*PlusK[wallpts[i]] = PlusK[pnts[i]];*

*printf("MinusK[%d] = %f\tPlusK[%d] = %f\tTheta[%d] = %f\tNu[%d] = %f\n",wallpts[i], MinusK[wallpts[i]], wallpts[i], PlusK[wallpts[i]], wallpts[i],theta[wallpts[i]], wallpts[i],Nu[wallpts[i]]);*

*}*

*total = n+1;*

*for(i=0; i<n-1; i++)*

*total = total + (n-i);*

*printf("\nTotal points = %d\n\n",total);*

*for(i=1, p=1; i<=(total-n); i++, p++)*

*{*

*for(j=0;j<n;j++)*

*{*

*if(p == wallpts[j])*

*{*

*jo = j;*

*break;*

*}*

*}*

*if(p == wallpts[j])*

*{*

*intpts[i] = ++p;*

*continue;*

*}*

*intpts[i] = p;*

*}*

*printf("\nThe Interior Points are:\n\n");*

*for(i=0; i<(total-n); i++)*

*{*

*intpts[i] = intpts[i+1];*

*printf("Intpts[%d] = %d\n",i,intpts[i]);*

*}*

*printf("\n Flow properties of Interior points on Characteristic line 1 are:\n");*

*for (i=0; i<n; i++)*

*{*

*theta[intpts[i]] = theta[pts[i]];*

*Nu[intpts[i]] = Nu[pts[i]];*

*MinusK[intpts[i]] = MinusK[pts[i]];*

*PlusK[intpts[i]] = PlusK[pts[i]];*

*printf("\nMinusK[%d] = %f\tPlusK[%d] = %f\tTheta[%d] = %f\tNu[%d] = %f\n",intpts[i], MinusK[intpts[i]], intpts[i], PlusK[intpts[i]], intpts[i],theta[intpts[i]], intpts[i],Nu[intpts[i]]);*

*for(i=0; i<n-1; i++)*

*{*

*printf("\n\n Flow properties of Interior points on Characteristic line %d are:\n ",++q);*

*theta[intpts[first]] = theta[points[i]];*

*Nu[intpts[first]] = Nu [points[i]];*

*MinusK[intpts[first]] = MinusK[points[i]];*

*PlusK[intpts[first]] = PlusK[points[i]];*

*first = first + (n-i);*

*printf("\nMinusK[%d] = %f\tPlusK[%d] = %f\tTheta[%d] = %f\tNu[%d] = %f\n",intpts[first], MinusK[intpts[first]], intpts[first], PlusK[intpts[first]], intpts[first],theta[intpts[first]], intpts[first],Nu[intpts[first]]);*

*second = second + (n-i);*

*for(j=0;j<(n-x);j++)*

*{*

*theta[intpts[second+j]] = (dt\*(j+1));*

*Nu[intpts[second+j]] = theta[intpts[second+j]] - PlusK[intpts[first]];*

*MinusK[intpts[second+j]] = theta[intpts[second+j]] + Nu[intpts[second+j]];*

*PlusK [intpts[second+j]] = theta[intpts[second+j]] - Nu[intpts[second+j]];*

*printf("\nMinusK[%d] = %f\tPlusK[%d] = %f\tTheta[%d] = %f\tNu[%d] = %f\n",intpts[second+j], MinusK[intpts[second+j]], intpts[second+j], PlusK[intpts[second+j]], intpts[second+j],theta[intpts[second+j]], intpts[second+j],Nu[intpts[second+j]]);*

*}*

*x=x+1;*

*}*

*printf("\n\n\n Flow properties of all Interior Points:\n");*

*for(i=0; i<(total-n); i++)*

*{*

*printf("\nMinusK[%d] = %f\tPlusK[%d] = %f\tTheta[%d] = %f\tNu[%d] = %f\n",intpts[i], MinusK[intpts[i]], intpts[i], PlusK[intpts[i]], intpts[i],theta[intpts[i]], intpts[i],Nu[intpts[i]]);*

*}*

*printf("\n\n\n Flow properties of the points on the Nozzle Wall:\n");*

*for (i=0; i<n; i++)*

*{*

*printf("\nMinusK[%d] = %f\tPlusK[%d] = %f\tTheta[%d] = %f\tNu[%d] = %f\n",wallpts[i], MinusK[wallpts[i]], wallpts[i], PlusK[wallpts[i]], wallpts[i],theta[wallpts[i]], wallpts[i],Nu[wallpts[i]]);*

*}*

*}*

## 

**Input:**

Design exit Mach number = 4.3

Throat wall angle = 34.77

Number of characteristics considered = 18

**Output:**

Using the above program , the flow properties at the axis line , wall points , first characteristic line (left running ) and last characteristic line (right running ) and all the remaining interior points of the grid were calculated.

The output obtained on the console was as follows:

*Enter the Design Exit Mach Number.*

*4.3*

*Enter the Flow Deflection Angle.*

*34.77*

*Enter the Number of Characteristics to be considered.*

*18*

*Rem=0.770000*

*The value of a=34.000000*

*Delta Theta = 2*

*The points on the First Left Running Characteristic line are as follows:*

*Pts[0] = 1*

*Pts[1] = 2*

*Pts[2] = 3*

*Pts[3] = 4*

*Pts[4] = 5*

*Pts[5] = 6*

*Pts[6] = 7*

*Pts[7] = 8*

*Pts[8] = 9*

*Pts[9] = 10*

*Pts[10] = 11*

*Pts[11] = 12*

*Pts[12] = 13*

*Pts[13] = 14*

*Pts[14] = 15*

*Pts[15] = 16*

*Pts[16] = 17*

*Pts[17] = 18*

***Flow properties of the points on the First Left Running Characteristic line:***

*Point 1 MinusK[1] = 1.540001 PlusK[1] = 0.000000 Theta[1] = 0.770000 Nu[1] = 0.770000*

*Point 2 MinusK[2] = 5.540001 PlusK[2] = 0.000000 Theta[2] = 2.770000 Nu[2] = 2.770000*

*Point 3 MinusK[3] = 9.540001 PlusK[3] = 0.000000 Theta[3] = 4.770000 Nu[3] = 4.770000*

*Point 4 MinusK[4] = 13.540001 PlusK[4] = 0.000000 Theta[4] = 6.770000 Nu[4] = 6.770000*

*Point 5 MinusK[5] = 17.540001 PlusK[5] = 0.000000 Theta[5] = 8.770000 Nu[5] = 8.770000*

*Point 6 MinusK[6] = 21.540001 PlusK[6] = 0.000000 Theta[6] = 10.770000 Nu[6] = 10.770000*

*Point 7 MinusK[7] = 25.540001 PlusK[7] = 0.000000 Theta[7] = 12.770000 Nu[7] = 12.770000*

*Point 8 MinusK[8] = 29.540001 PlusK[8] = 0.000000 Theta[8] = 14.770000 Nu[8] = 14.770000*

*Point 9 MinusK[9] = 33.540001 PlusK[9] = 0.000000 Theta[9] = 16.770000 Nu[9] = 16.770000*

*Point 10 MinusK[10] = 37.540001 PlusK[10] = 0.000000 Theta[10] = 18.770000 Nu[10] = 18.770000*

*Point 11 MinusK[11] = 41.540001 PlusK[11] = 0.000000 Theta[11] = 20.770000 Nu[11] = 20.770000*

*Point 12 MinusK[12] = 45.540001 PlusK[12] = 0.000000 Theta[12] = 22.770000 Nu[12] = 22.770000*

*Point 13 MinusK[13] = 49.540001 PlusK[13] = 0.000000 Theta[13] = 24.770000 Nu[13] = 24.770000*

*Point 14 MinusK[14] = 53.540001 PlusK[14] = 0.000000 Theta[14] = 26.770000 Nu[14] = 26.770000*

*Point 15 MinusK[15] = 57.540001 PlusK[15] = 0.000000 Theta[15] = 28.770000 Nu[15] = 28.770000*

*Point 16 MinusK[16] = 61.540001 PlusK[16] = 0.00000 Theta[16] = 30.770000 Nu[16] = 30.770000*

*Point 17 MinusK[17] = 65.540001 PlusK[17] = 0.000000 Theta[17] = 32.770000 Nu[17] = 32.770000*

*Point 18 MinusK[18] = 69.540001 PlusK[18] = 0.000000 Theta[18] = 34.770000 Nu[18] = 34.770000*

***The points on the Axis line are as follows:***

*Points[0] = 1*

*Points[1] = 20*

*Points[2] = 38*

*Points[3] = 55*

*Points[4] = 71*

*Points[5] = 86*

*Points[6] = 100*

*Points[7] = 113*

*Points[8] = 125*

*Points[9] = 136*

*Points[10] = 146*

*Points[11] = 155*

*Points[12] = 163*

*Points[13] = 170*

*Points[14] = 176*

*Points[15] = 181*

*Points[16] = 185*

*Points[17] = 188*

***Flow properties of the points on the Axis line:***

*MinusK[1] = 1.540001 PlusK[1] = 0.000000 Theta[1] = 0.770000 Nu[1] = 0.770000*

*MinusK[20] = 5.540001 PlusK[20] = -5.540001 Theta[20] = 0.000000 Nu[20] = 5.540001*

*MinusK[38] = 9.540001 PlusK[38] = -9.540001 Theta[38] = 0.000000 Nu[38] = 9.540001*

*MinusK[55] = 13.540001 PlusK[55] = -13.540001 Theta[55] = 0.000000 Nu[55] = 13.540001*

*MinusK[71] = 17.540001 PlusK[71] = -17.540001 Theta[71] = 0.000000 Nu[71] = 17.540001*

*MinusK[86] = 21.540001 PlusK[86] = -21.540001 Theta[86] = 0.000000 Nu[86] = 21.540001*

*MinusK[100] = 25.540001 PlusK[100] = -25.540001 Theta[100] = 0.000000 Nu[100] = 25.540001*

*MinusK[113] = 29.540001 PlusK[113] = -29.540001 Theta[113] = 0.000000 Nu[113] = 29.540001*

*MinusK[125] = 33.540001 PlusK[125] = -33.540001 Theta[125] = 0.000000 Nu[125] = 33.540001*

*MinusK[136] = 37.540001 PlusK[136] = -37.540001 Theta[136] = 0.000000 Nu[136] = 37.540001*

*MinusK[146] = 41.540001 PlusK[146] = -41.540001 Theta[146] = 0.000000 Nu[146] = 41.540001*

*MinusK[155] = 45.540001 PlusK[155] = -45.540001 Theta[155] = 0.000000 Nu[155] = 45.540001*

*MinusK[163] = 49.540001 PlusK[163] = -49.540001 Theta[163] = 0.000000 Nu[163] = 49.540001*

*MinusK[170] = 53.540001 PlusK[170] = -53.540001 Theta[170] = 0.000000 Nu[170] = 53.540001*

*MinusK[176] = 57.540001 PlusK[176] = -57.540001 Theta[176] = 0.000000 Nu[176] = 57.540001*

*MinusK[181] = 61.540001 PlusK[181] = -61.540001 Theta[181] = 0.000000 Nu[181] = 61.540001*

*MinusK[185] = 65.540001 PlusK[185] = -65.540001 Theta[185] = 0.000000 Nu[185] = 65.540001*

*MinusK[188] = 69.540001 PlusK[188] = -69.540001 Theta[188] = 0.000000 Nu[188] = 69.540001*

***The points on the Last Right Running Characteristic line:***

*Pnts[0] = 18*

*Pnts[1] = 36*

*Pnts[2] = 53*

*Pnts[3] = 69*

*Pnts[4] = 84*

*Pnts[5] = 98*

*Pnts[6] = 111*

*Pnts[7] = 123*

*Pnts[8] = 134*

*Pnts[9] = 144*

*Pnts[10] = 153*

*Pnts[11] = 161*

*Pnts[12] = 168*

*Pnts[13] = 174*

*Pnts[14] = 179*

*Pnts[15] = 183*

*Pnts[16] = 186*

*Pnts[17] = 188*

***Flow properties of the points on the Last Right Running Characteristic line:***

*MinusK[ 18] = 69.540001 PlusK[ 18] = 0.000000 Theta[ 18] = 34.770000 Nu[ 18] = 34.770000*

*MinusK[36] = 69.540001 PlusK[36] = -5.540001 Theta[36] = 32.000000 Nu[36] = 37.540001*

*MinusK[53] = 69.540001 PlusK[53] = -9.540001 Theta[53] = 30.000000 Nu[53] = 39.540001*

*MinusK[69] = 69.540001 PlusK[69] = -13.540001 Theta[69] = 28.000000 Nu[69] = 41.540001*

*MinusK[84] = 69.540001 PlusK[84] = -17.540001 Theta[84] = 26.000000 Nu[84] = 43.540001*

*MinusK[98] = 69.540001 PlusK[98] = -21.540001 Theta[98] = 24.000000 Nu[98] = 45.540001*

*MinusK[111] = 69.540001 PlusK[111] = -25.540001 Theta[111] = 22.000000 Nu[111] = 47.540001*

*MinusK[123] = 69.540001 PlusK[123] = -29.540001 Theta[123] = 20.000000 Nu[123] = 49.540001*

*MinusK[134] = 69.540001 PlusK[134] = -33.540001 Theta[134] = 18.000000 Nu[134] = 51.540001*

*MinusK[144] = 69.540001 PlusK[144] = -37.540001 Theta[144] = 16.000000 Nu[144] = 53.540001*

*MinusK[153] = 69.540001 PlusK[153] = -41.540001 Theta[153] = 14.000000 Nu[153] = 55.540001*

*MinusK[161] = 69.540001 PlusK[161] = -45.540001 Theta[161] = 12.000000 Nu[161] = 57.540001*

*MinusK[168] = 69.540001 PlusK[168] = -49.540001 Theta[168] = 10.000000 Nu[168] = 59.540001*

*MinusK[174] = 69.540001 PlusK[174] = -53.540001 Theta[174] = 8.000000 Nu[174] = 61.540001*

*MinusK[179] = 69.540001 PlusK[179] = -57.540001 Theta[179] = 6.000000 Nu[179] = 63.540001*

*MinusK[183] = 69.540001 PlusK[183] = -61.540001 Theta[183] = 4.000000 Nu[183] = 65.540001*

*MinusK[186] = 69.540001 PlusK[186] = -65.540001 Theta[186] = 2.000000 Nu[186] = 67.540001*

*MinusK[188] = 69.540001 PlusK[188] = -69.540001 Theta[188] = 0.000000 Nu[188] = 69.540001*

***The points on the Nozzle Wall:***

*WallPts[0] = 19*

*WallPts[1] = 37*

*WallPts[2] = 54*

*WallPts[3] = 70*

*WallPts[4] = 85*

*WallPts[5] = 99*

*WallPts[6] = 112*

*WallPts[7] = 124*

*WallPts[8] = 135*

*WallPts[9] = 145*

*WallPts[10] = 154*

*WallPts[11] = 162*

*WallPts[12] = 169*

*WallPts[13] = 175*

*WallPts[14] = 180*

*WallPts[15] = 184*

*WallPts[16] = 187*

*WallPts[17] = 189*

***Flow properties of the points on the Nozzle Wall:***

*MinusK[19] = 69.540001 PlusK[19] = 0.000000 Theta[19] = 34.770000 Nu[19] = 34.770000*

*MinusK[37] = 69.540001 PlusK[37] = -5.540001 Theta[37] = 32.000000 Nu[37] = 37.540001*

*MinusK[54] = 69.540001 PlusK[54] = -9.540001 Theta[54] = 30.000000 Nu[54] = 39.540001*

*MinusK[70] = 69.540001 PlusK[70] = -13.540001 Theta[70] = 28.000000 Nu[70] = 41.540001*

*MinusK[85] = 69.540001 PlusK[85] = -17.540001 Theta[85] = 26.000000 Nu[85] = 43.540001*

*MinusK[99] = 69.540001 PlusK[99] = -21.540001 Theta[99] = 24.000000 Nu[99] = 45.540001*

*MinusK[112] = 69.540001 PlusK[112] = -25.540001 Theta[112] = 22.000000 Nu[112] = 47.540001*

*MinusK[124] = 69.540001 PlusK[124] = -29.540001 Theta[124] = 20.000000 Nu[124] = 49.540001*

*MinusK[135] = 69.540001 PlusK[135] = -33.540001 Theta[135] = 18.000000 Nu[135] = 51.540001*

*MinusK[145] = 69.540001 PlusK[145] = -37.540001 Theta[145] = 16.000000 Nu[145] = 53.540001*

*MinusK[154] = 69.540001 PlusK[154] = -41.540001 Theta[154] = 14.000000 Nu[154] = 55.540001*

*MinusK[162] = 69.540001 PlusK[162] = -45.540001 Theta[162] = 12.000000 Nu[162] = 57.540001*

*MinusK[169] = 69.540001 PlusK[169] = -49.540001 Theta[169] = 10.000000 Nu[169] = 59.540001*

*MinusK[175] = 69.540001 PlusK[175] = -53.540001 Theta[175] = 8.000000 Nu[175] = 61.540001*

*MinusK[180] = 69.540001 PlusK[180] = -57.540001 Theta[180] = 6.000000 Nu[180] = 63.540001*

*MinusK[184] = 69.540001 PlusK[184] = -61.540001 Theta[184] = 4.000000 Nu[184] = 65.540001*

*MinusK[187] = 69.540001 PlusK[187] = -65.540001 Theta[187] = 2.000000 Nu[187] = 67.540001*

*MinusK[189] = 69.540001 PlusK[189] = -69.540001 Theta[189] = 0.000000 Nu[189] = 69.540001*

*Total points = 189*

***The Interior Points are:***

*Intpts[0] = 1*

*Intpts[1] = 2*

*Intpts[2] = 3*

*Intpts[3] = 4*

*Intpts[4] = 5*

*Intpts[5] = 6*

*Intpts[6] = 7*

*Intpts[7] = 8*

*Intpts[8] = 9*

*Intpts[9] = 10*

*Intpts[10] = 11*

*Intpts[11] = 12*

*Intpts[12] = 13*

*Intpts[13] = 14*

*Intpts[14] = 15*

*Intpts[15] = 16*

*Intpts[16] = 17*

*Intpts[17] = 18*

*Intpts[18] = 20*

*Intpts[19] = 21*

*Intpts[20] = 22*

*Intpts[21] = 23*

*Intpts[22] = 24*

*Intpts[23] = 25*

*Intpts[24] = 26*

*Intpts[25] = 27*

*Intpts[26] = 28*

*Intpts[27] = 29*

*Intpts[28] = 30*

*Intpts[29] = 31*

*Intpts[30] = 32*

*Intpts[31] = 33*

*Intpts[32] = 34*

*Intpts[33] = 35*

*Intpts[34] = 36*

*Intpts[35] = 38*

*Intpts[36] = 39*

*Intpts[37] = 40*

*Intpts[38] = 41*

*Intpts[39] = 42*

*Intpts[40] = 43*

*Intpts[41] = 44*

*Intpts[42] = 45*

*Intpts[43] = 46*

*Intpts[44] = 47*

*Intpts[45] = 48*

*Intpts[46] = 49*

*Intpts[47] = 50*

*Intpts[48] = 51*

*Intpts[49] = 52*

*Intpts[50] = 53*

*Intpts[51] = 55*

*Intpts[52] = 56*

*Intpts[53] = 57*

*Intpts[54] = 58*

*Intpts[55] = 59*

*Intpts[56] = 60*

*Intpts[57] = 61*

*Intpts[58] = 62*

*Intpts[59] = 63*

*Intpts[60] = 64*

*Intpts[61] = 65*

*Intpts[62] = 66*

*Intpts[63] = 67*

*Intpts[64] = 68*

*Intpts[65] = 69*

*Intpts[66] = 71*

*Intpts[67] = 72*

*Intpts[68] = 73*

*Intpts[69] = 74*

*Intpts[70] = 75*

*Intpts[71] = 76*

*Intpts[72] = 77*

*Intpts[73] = 78*

*Intpts[74] = 79*

*Intpts[75] = 80*

*Intpts[76] = 81*

*Intpts[77] = 82*

*Intpts[78] = 83*

*Intpts[79] = 84*

*Intpts[80] = 86*

*Intpts[81] = 87*

*Intpts[82] = 88*

*Intpts[83] = 89*

*Intpts[84] = 90*

*Intpts[85] = 91*

*Intpts[86] = 92*

*Intpts[87] = 93*

*Intpts[88] = 94*

*Intpts[89] = 95*

*Intpts[90] = 96*

*Intpts[91] = 97*

*Intpts[92] = 98*

*Intpts[93] = 100*

*Intpts[94] = 101*

*Intpts[95] = 102*

*Intpts[96] = 103*

*Intpts[97] = 104*

*Intpts[98] = 105*

*Intpts[99] = 106*

*Intpts[100] = 107*

*Intpts[101] = 108*

*Intpts[102] = 109*

*Intpts[103] = 110*

*Intpts[104] = 111*

*Intpts[105] = 113*

*Intpts[106] = 114*

*Intpts[107] = 115*

*Intpts[108] = 116*

*Intpts[109] = 117*

*Intpts[110] = 118*

*Intpts[111] = 119*

*Intpts[112] = 120*

*Intpts[113] = 121*

*Intpts[114] = 122*

*Intpts[115] = 123*

*Intpts[116] = 125*

*Intpts[117] = 126*

*Intpts[118] = 127*

*Intpts[119] = 128*

*Intpts[120] = 129*

*Intpts[121] = 130*

*Intpts[122] = 131*

*Intpts[123] = 132*

*Intpts[124] = 133*

*Intpts[125] = 134*

*Intpts[126] = 136*

*Intpts[127] = 137*

*Intpts[128] = 138*

*Intpts[129] = 139*

*Intpts[130] = 140*

*Intpts[131] = 141*

*Intpts[132] = 142*

*Intpts[133] = 143*

*Intpts[134] = 144*

*Intpts[135] = 146*

*Intpts[136] = 147*

*Intpts[137] = 148*

*Intpts[138] = 149*

*Intpts[139] = 150*

*Intpts[140] = 151*

*Intpts[141] = 152*

*Intpts[142] = 153*

*Intpts[143] = 155*

*Intpts[144] = 156*

*Intpts[145] = 157*

*Intpts[146] = 158*

*Intpts[147] = 159*

*Intpts[148] = 160*

*Intpts[149] = 161*

*Intpts[150] = 163*

*Intpts[151] = 164*

*Intpts[152] = 165*

*Intpts[153] = 166*

*Intpts[154] = 167*

*Intpts[155] = 168*

*Intpts[156] = 170*

*Intpts[157] = 171*

*Intpts[158] = 172*

*Intpts[159] = 173*

*Intpts[160] = 174*

*Intpts[161] = 176*

*Intpts[162] = 177*

*Intpts[163] = 178*

*Intpts[164] = 179*

*Intpts[165] = 181*

*Intpts[166] = 182*

*Intpts[167] = 183*

*Intpts[168] = 185*

*Intpts[169] = 186*

*Intpts[170] = 188*

***Flow properties of Interior points on Characteristic line 1 are:***

*MinusK[1] = 1.540001 PlusK[1] = 0.000000 Theta[1] = 0.770000 Nu[1] = 0.770000*

*MinusK[2] = 5.540001 PlusK[2] = 0.000000 Theta[2] = 2.770000 Nu[2] = 2.770000*

*MinusK[3] = 9.540001 PlusK[3] = 0.000000 Theta[3] = 4.770000 Nu[3] = 4.770000*

*MinusK[4] = 13.540001 PlusK[4] = 0.000000 Theta[4] = 6.770000 Nu[4] = 6.770000*

*MinusK[5] = 17.540001 PlusK[5] = 0.000000 Theta[5] = 8.770000 Nu[5] = 8.770000*

*MinusK[6] = 21.540001 PlusK[6] = 0.000000 Theta[6] = 10.770000 Nu[6] = 10.770000*

*MinusK[7] = 25.540001 PlusK[7] = 0.000000 Theta[7] = 12.770000 Nu[7] = 12.770000*

*MinusK[8] = 29.540001 PlusK[8] = 0.000000 Theta[8] = 14.770000 Nu[8] = 14.770000*

*MinusK[9] = 33.540001 PlusK[9] = 0.000000 Theta[9] = 16.770000 Nu[9] = 16.770000*

*MinusK[10] = 37.540001 PlusK[10] = 0.000000 Theta[10] = 18.770000 Nu[10] = 18.770000*

*MinusK[11] = 41.540001 PlusK[11] = 0.000000 Theta[11] = 20.770000 Nu[11] = 20.770000*

*MinusK[12] = 45.540001 PlusK[12] = 0.000000 Theta[12] = 22.770000 Nu[12] = 22.770000*

*MinusK[13] = 49.540001 PlusK[13] = 0.000000 Theta[13] = 24.770000 Nu[13] = 24.770000*

*MinusK[14] = 53.540001 PlusK[14] = 0.000000 Theta[14] = 26.770000 Nu[14] = 26.770000*

*MinusK[15] = 57.540001 PlusK[15] = 0.000000 Theta[15] = 28.770000 Nu[15] = 28.770000*

*MinusK[16] = 61.540001 PlusK[16] = 0.000000 Theta[16] = 30.770000 Nu[16] = 30.770000*

*MinusK[17] = 65.540001 PlusK[17] = 0.000000 Theta[17] = 32.770000 Nu[17] = 32.770000*

*MinusK[18] = 69.540001 PlusK[18] = 0.000000 Theta[18] = 34.770000 Nu[18] = 34.770000*

***Flow properties of Interior points on Characteristic line 2 are:***

*MinusK[20] = 5.540001 PlusK[20] = -5.540001 Theta[20] = 0.000000 Nu[20] = 5.540001*

*MinusK[21] = 9.540001 PlusK[21] = -5.540001 Theta[21] = 2.000000 Nu[21] = 7.540001*

*MinusK[22] = 13.540001 PlusK[22] = -5.540001 Theta[22] = 4.000000 Nu[22] = 9.540001*

*MinusK[23] = 17.540001 PlusK[23] = -5.540001 Theta[23] = 6.000000 Nu[23] = 11.540001*

*MinusK[24] = 21.540001 PlusK[24] = -5.540001 Theta[24] = 8.000000 Nu[24] = 13.540001*

*MinusK[25] = 25.540001 PlusK[25] = -5.540001 Theta[25] = 10.000000 Nu[25] = 15.540001*

*MinusK[26] = 29.540001 PlusK[26] = -5.540001 Theta[26] = 12.000000 Nu[26] = 17.540001*

*MinusK[27] = 33.540001 PlusK[27] = -5.540001 Theta[27] = 14.000000 Nu[27] = 19.540001*

*MinusK[28] = 37.540001 PlusK[28] = -5.540001 Theta[28] = 16.000000 Nu[28] = 21.540001*

*MinusK[29] = 41.540001 PlusK[29] = -5.540001 Theta[29] = 18.000000 Nu[29] = 23.540001*

*MinusK[30] = 45.540001 PlusK[30] = -5.540001 Theta[30] = 20.000000 Nu[30] = 25.540001*

*MinusK[31] = 49.540001 PlusK[31] = -5.540001 Theta[31] = 22.000000 Nu[31] = 27.540001*

*MinusK[32] = 53.540001 PlusK[32] = -5.540001 Theta[32] = 24.000000 Nu[32] = 29.540001*

*MinusK[33] = 57.540001 PlusK[33] = -5.540001 Theta[33] = 26.000000 Nu[33] = 31.540001*

*MinusK[34] = 61.540001 PlusK[34] = -5.540001 Theta[34] = 28.000000 Nu[34] = 33.540001*

*MinusK[35] = 65.540001 PlusK[35] = -5.540001 Theta[35] = 30.000000 Nu[35] = 35.540001*

*MinusK[36] = 69.540001 PlusK[36] = -5.540001 Theta[36] = 32.000000 Nu[36] = 37.540001*

***Flow properties of Interior points on Characteristic line 3 are:***

*MinusK[38] = 9.540001 PlusK[38] = -9.540001 Theta[38] = 0.000000 Nu[38] = 9.540001*

*MinusK[39] = 13.540001 PlusK[39] = -9.540001 Theta[39] = 2.000000 Nu[39] = 11.540001*

*MinusK[40] = 17.540001 PlusK[40] = -9.540001 Theta[40] = 4.000000 Nu[40] = 13.540001*

*MinusK[41] = 21.540001 PlusK[41] = -9.540001 Theta[41] = 6.000000 Nu[41] = 15.540001*

*MinusK[42] = 25.540001 PlusK[42] = -9.540001 Theta[42] = 8.000000 Nu[42] = 17.540001*

*MinusK[43] = 29.540001 PlusK[43] = -9.540001 Theta[43] = 10.000000 Nu[43] = 19.540001*

*MinusK[44] = 33.540001 PlusK[44] = -9.540001 Theta[44] = 12.000000 Nu[44] = 21.540001*

*MinusK[45] = 37.540001 PlusK[45] = -9.540001 Theta[45] = 14.000000 Nu[45] = 23.540001*

*MinusK[46] = 41.540001 PlusK[46] = -9.540001 Theta[46] = 16.000000 Nu[46] = 25.540001*

*MinusK[47] = 45.540001 PlusK[47] = -9.540001 Theta[47] = 18.000000 Nu[47] = 27.540001*

*MinusK[48] = 49.540001 PlusK[48] = -9.540001 Theta[48] = 20.000000 Nu[48] = 29.540001*

*MinusK[49] = 53.540001 PlusK[49] = -9.540001 Theta[49] = 22.000000 Nu[49] = 31.540001*

*MinusK[50] = 57.540001 PlusK[50] = -9.540001 Theta[50] = 24.000000 Nu[50] = 33.540001*

*MinusK[51] = 61.540001 PlusK[51] = -9.540001 Theta[51] = 26.000000 Nu[51] = 35.540001*

*MinusK[52] = 65.540001 PlusK[52] = -9.540001 Theta[52] = 28.000000 Nu[52] = 37.540001*

*MinusK[53] = 69.540001 PlusK[53] = -9.540001 Theta[53] = 30.000000 Nu[53] = 39.540001*

***Flow properties of Interior points on Characteristic line 4 are:***

*MinusK[55] = 13.540001 PlusK[55] = -13.540001 Theta[55] = 0.000000 Nu[55] = 13.540001*

*MinusK[56] = 17.540001 PlusK[56] = -13.540001 Theta[56] = 2.000000 Nu[56] = 15.540001*

*MinusK[57] = 21.540001 PlusK[57] = -13.540001 Theta[57] = 4.000000 Nu[57] = 17.540001*

*MinusK[58] = 25.540001 PlusK[58] = -13.540001 Theta[58] = 6.000000 Nu[58] = 19.540001*

*MinusK[59] = 29.540001 PlusK[59] = -13.540001 Theta[59] = 8.000000 Nu[59] = 21.540001*

*MinusK[60] = 33.540001 PlusK[60] = -13.540001 Theta[60] = 10.000000 Nu[60] = 23.540001*

*MinusK[61] = 37.540001 PlusK[61] = -13.540001 Theta[61] = 12.000000 Nu[61] = 25.540001*

*MinusK[62] = 41.540001 PlusK[62] = -13.540001 Theta[62] = 14.000000 Nu[62] = 27.540001*

*MinusK[63] = 45.540001 PlusK[63] = -13.540001 Theta[63] = 16.000000 Nu[63] = 29.540001*

*MinusK[64] = 49.540001 PlusK[64] = -13.540001 Theta[64] = 18.000000 Nu[64] = 31.540001*

*MinusK[65] = 53.540001 PlusK[65] = -13.540001 Theta[65] = 20.000000 Nu[65] = 33.540001*

*MinusK[66] = 57.540001 PlusK[66] = -13.540001 Theta[66] = 22.000000 Nu[66] = 35.540001*

*MinusK[67] = 61.540001 PlusK[67] = -13.540001 Theta[67] = 24.000000 Nu[67] = 37.540001*

*MinusK[68] = 65.540001 PlusK[68] = -13.540001 Theta[68] = 26.000000 Nu[68] = 39.540001*

*MinusK[69] = 69.540001 PlusK[69] = -13.540001 Theta[69] = 28.000000 Nu[69] = 41.540001*

***Flow properties of Interior points on Characteristic line 5 are:***

*MinusK[71] = 17.540001 PlusK[71] = -17.540001 Theta[71] = 0.000000 Nu[71] = 17.540001*

*MinusK[72] = 21.540001 PlusK[72] = -17.540001 Theta[72] = 2.000000 Nu[72] = 19.540001*

*MinusK[73] = 25.540001 PlusK[73] = -17.540001 Theta[73] = 4.000000 Nu[73] = 21.540001*

*MinusK[74] = 29.540001 PlusK[74] = -17.540001 Theta[74] = 6.000000 Nu[74] = 23.540001*

*MinusK[75] = 33.540001 PlusK[75] = -17.540001 Theta[75] = 8.000000 Nu[75] = 25.540001*

*MinusK[76] = 37.540001 PlusK[76] = -17.540001 Theta[76] = 10.000000 Nu[76] = 27.540001*

*MinusK[77] = 41.540001 PlusK[77] = -17.540001 Theta[77] = 12.000000 Nu[77] = 29.540001*

*MinusK[78] = 45.540001 PlusK[78] = -17.540001 Theta[78] = 14.000000 Nu[78] = 31.540001*

*MinusK[79] = 49.540001 PlusK[79] = -17.540001 Theta[79] = 16.000000 Nu[79] = 33.540001*

*MinusK[80] = 53.540001 PlusK[80] = -17.540001 Theta[80] = 18.000000 Nu[80] = 35.540001*

*MinusK[81] = 57.540001 PlusK[81] = -17.540001 Theta[81] = 20.000000 Nu[81] = 37.540001*

*MinusK[82] = 61.540001 PlusK[82] = -17.540001 Theta[82] = 22.000000 Nu[82] = 39.540001*

*MinusK[83] = 65.540001 PlusK[83] = -17.540001 Theta[83] = 24.000000 Nu[83] = 41.540001*

*MinusK[84] = 69.540001 PlusK[84] = -17.540001 Theta[84] = 26.000000 Nu[84] = 43.540001*

***Flow properties of Interior points on Characteristic line 6 are:***

*MinusK[86] = 21.540001 PlusK[86] = -21.540001 Theta[86] = 0.000000 Nu[86] = 21.540001*

*MinusK[87] = 25.540001 PlusK[87] = -21.540001 Theta[87] = 2.000000 Nu[87] = 23.540001*

*MinusK[88] = 29.540001 PlusK[88] = -21.540001 Theta[88] = 4.000000 Nu[88] = 25.540001*

*MinusK[89] = 33.540001 PlusK[89] = -21.540001 Theta[89] = 6.000000 Nu[89] = 27.540001*

*MinusK[90] = 37.540001 PlusK[90] = -21.540001 Theta[90] = 8.000000 Nu[90] = 29.540001*

*MinusK[91] = 41.540001 PlusK[91] = -21.540001 Theta[91] = 10.000000 Nu[91] = 31.540001*

*MinusK[92] = 45.540001 PlusK[92] = -21.540001 Theta[92] = 12.000000 Nu[92] = 33.540001*

*MinusK[93] = 49.540001 PlusK[93] = -21.540001 Theta[93] = 14.000000 Nu[93] = 35.540001*

*MinusK[94] = 53.540001 PlusK[94] = -21.540001 Theta[94] = 16.000000 Nu[94] = 37.540001*

*MinusK[95] = 57.540001 PlusK[95] = -21.540001 Theta[95] = 18.000000 Nu[95] = 39.540001*

*MinusK[96] = 61.540001 PlusK[96] = -21.540001 Theta[96] = 20.000000 Nu[96] = 41.540001*

*MinusK[97] = 65.540001 PlusK[97] = -21.540001 Theta[97] = 22.000000 Nu[97] = 43.540001*

*MinusK[98] = 69.540001 PlusK[98] = -21.540001 Theta[98] = 24.000000 Nu[98] = 45.540001*

***Flow properties of Interior points on Characteristic line 7 are:***

*MinusK[100] = 25.540001 PlusK[100] = -25.540001 Theta[100] = 0.000000 Nu[100] = 25.540001*

*MinusK[101] = 29.540001 PlusK[101] = -25.540001 Theta[101] = 2.000000 Nu[101] = 27.540001*

*MinusK[102] = 33.540001 PlusK[102] = -25.540001 Theta[102] = 4.000000 Nu[102] = 29.540001*

*MinusK[103] = 37.540001 PlusK[103] = -25.540001 Theta[103] = 6.000000 Nu[103] = 31.540001*

*MinusK[104] = 41.540001 PlusK[104] = -25.540001 Theta[104] = 8.000000 Nu[104] = 33.540001*

*MinusK[105] = 45.540001 PlusK[105] = -25.540001 Theta[105] = 10.000000 Nu[105] = 35.540001*

*MinusK[106] = 49.540001 PlusK[106] = -25.540001 Theta[106] = 12.000000 Nu[106] = 37.540001*

*MinusK[107] = 53.540001 PlusK[107] = -25.540001 Theta[107] = 14.000000 Nu[107] = 39.540001*

*MinusK[108] = 57.540001 PlusK[108] = -25.540001 Theta[108] = 16.000000 Nu[108] = 41.540001*

*MinusK[109] = 61.540001 PlusK[109] = -25.540001 Theta[109] = 18.000000 Nu[109] = 43.540001*

*MinusK[110] = 65.540001 PlusK[110] = -25.540001 Theta[110] = 20.000000 Nu[110] = 45.540001*

*MinusK[111] = 69.540001 PlusK[111] = -25.540001 Theta[111] = 22.000000 Nu[111] = 47.540001*

***Flow properties of Interior points on Characteristic line 8 are:***

*MinusK[113] = 29.540001 PlusK[113] = -29.540001 Theta[113] = 0.000000 Nu[113] = 29.540001*

*MinusK[114] = 33.540001 PlusK[114] = -29.540001 Theta[114] = 2.000000 Nu[114] = 31.540001*

*MinusK[115] = 37.540001 PlusK[115] = -29.540001 Theta[115] = 4.000000 Nu[115] = 33.540001*

*MinusK[116] = 41.540001 PlusK[116] = -29.540001 Theta[116] = 6.000000 Nu[116] = 35.540001*

*MinusK[117] = 45.540001 PlusK[117] = -29.540001 Theta[117] = 8.000000 Nu[117] = 37.540001*

*MinusK[118] = 49.540001 PlusK[118] = -29.540001 Theta[118] = 10.000000 Nu[118] = 39.540001*

*MinusK[119] = 53.540001 PlusK[119] = -29.540001 Theta[119] = 12.000000 Nu[119] = 41.540001*

*MinusK[120] = 57.540001 PlusK[120] = -29.540001 Theta[120] = 14.000000 Nu[120] = 43.540001*

*MinusK[121] = 61.540001 PlusK[121] = -29.540001 Theta[121] = 16.000000 Nu[121] = 45.540001*

*MinusK[122] = 65.540001 PlusK[122] = -29.540001 Theta[122] = 18.000000 Nu[122] = 47.540001*

*MinusK[123] = 69.540001 PlusK[123] = -29.540001 Theta[123] = 20.000000 Nu[123] = 49.540001*

***Flow properties of Interior points on Characteristic line 9 are:***

*MinusK[125] = 33.540001 PlusK[125] = -33.540001 Theta[125] = 0.000000 Nu[125] = 33.540001*

*MinusK[126] = 37.540001 PlusK[126] = -33.540001 Theta[126] = 2.000000 Nu[126] = 35.540001*

*MinusK[127] = 41.540001 PlusK[127] = -33.540001 Theta[127] = 4.000000 Nu[127] = 37.540001*

*MinusK[128] = 45.540001 PlusK[128] = -33.540001 Theta[128] = 6.000000 Nu[128] = 39.540001*

*MinusK[129] = 49.540001 PlusK[129] = -33.540001 Theta[129] = 8.000000 Nu[129] = 41.540001*

*MinusK[130] = 53.540001 PlusK[130] = -33.540001 Theta[130] = 10.000000 Nu[130] = 43.540001*

*MinusK[131] = 57.540001 PlusK[131] = -33.540001 Theta[131] = 12.000000 Nu[131] = 45.540001*

*MinusK[132] = 61.540001 PlusK[132] = -33.540001 Theta[132] = 14.000000 Nu[132] = 47.540001*

*MinusK[133] = 65.540001 PlusK[133] = -33.540001 Theta[133] = 16.000000 Nu[133] = 49.540001*

*MinusK[134] = 69.540001 PlusK[134] = -33.540001 Theta[134] = 18.000000 Nu[134] = 51.54000*

***Flow properties of Interior points on Characteristic line 10 are:***

*MinusK[136] = 37.540001 PlusK[136] = -37.540001 Theta[136] = 0.000000 Nu[136] = 37.540001*

*MinusK[137] = 41.540001 PlusK[137] = -37.540001 Theta[137] = 2.000000 Nu[137] = 39.540001*

*MinusK[138] = 45.540001 PlusK[138] = -37.540001 Theta[138] = 4.000000 Nu[138] = 41.540001*

*MinusK[139] = 49.540001 PlusK[139] = -37.540001 Theta[139] = 6.000000 Nu[139] = 43.540001*

*MinusK[140] = 53.540001 PlusK[140] = -37.540001 Theta[140] = 8.000000 Nu[140] = 45.540001*

*MinusK[141] = 57.540001 PlusK[141] = -37.540001 Theta[141] = 10.000000 Nu[141] = 47.540001*

*MinusK[142] = 61.540001 PlusK[142] = -37.540001 Theta[142] = 12.000000 Nu[142] = 49.540001*

*MinusK[143] = 65.540001 PlusK[143] = -37.540001 Theta[143] = 14.000000 Nu[143] = 51.540001*

*MinusK[144] = 69.540001 PlusK[144] = -37.540001 Theta[144] = 16.000000 Nu[144] = 53.540001*

***Flow properties of Interior points on Characteristic line 11 are:***

*MinusK[146] = 41.540001 PlusK[146] = -41.540001 Theta[146] = 0.000000 Nu[146] = 41.540001*

*MinusK[147] = 45.540001 PlusK[147] = -41.540001 Theta[147] = 2.000000 Nu[147] = 43.540001*

*MinusK[148] = 49.540001 PlusK[148] = -41.540001 Theta[148] = 4.000000 Nu[148] = 45.540001*

*MinusK[149] = 53.540001 PlusK[149] = -41.540001 Theta[149] = 6.000000 Nu[149] = 47.540001*

*MinusK[150] = 57.540001 PlusK[150] = -41.540001 Theta[150] = 8.000000 Nu[150] = 49.540001*

*MinusK[151] = 61.540001 PlusK[151] = -41.540001 Theta[151] = 10.000000 Nu[151] = 51.540001*

*MinusK[152] = 65.540001 PlusK[152] = -41.540001 Theta[152] = 12.000000 Nu[152] = 53.540001*

*MinusK[153] = 69.540001 PlusK[153] = -41.540001 Theta[153] = 14.000000 Nu[153] = 55.540001*

***Flow properties of Interior points on Characteristic line 12 are:***

*MinusK[155] = 45.540001 PlusK[155] = -45.540001 Theta[155] = 0.000000 Nu[155] = 45.540001*

*MinusK[156] = 49.540001 PlusK[156] = -45.540001 Theta[156] = 2.000000 Nu[156] = 47.540001*

*MinusK[157] = 53.540001 PlusK[157] = -45.540001 Theta[157] = 4.000000 Nu[157] = 49.540001*

*MinusK[158] = 57.540001 PlusK[158] = -45.540001 Theta[158] = 6.000000 Nu[158] = 51.540001*

*MinusK[159] = 61.540001 PlusK[159] = -45.540001 Theta[159] = 8.000000 Nu[159] = 53.540001*

*MinusK[160] = 65.540001 PlusK[160] = -45.540001 Theta[160] = 10.000000 Nu[160] = 55.540001*

*MinusK[161] = 69.540001 PlusK[161] = -45.540001 Theta[161] = 12.000000 Nu[161] = 57.540001*

***Flow properties of Interior points on Characteristic line 13 are:***

*MinusK[163] = 49.540001 PlusK[163] = -49.540001 Theta[163] = 0.000000 Nu[163] = 49.540001*

*MinusK[164] = 53.540001 PlusK[164] = -49.540001 Theta[164] = 2.000000 Nu[164] = 51.540001*

*MinusK[165] = 57.540001 PlusK[165] = -49.540001 Theta[165] = 4.000000 Nu[165] = 53.540001*

*MinusK[166] = 61.540001 PlusK[166] = -49.540001 Theta[166] = 6.000000 Nu[166] = 55.540001*

*MinusK[167] = 65.540001 PlusK[167] = -49.540001 Theta[167] = 8.000000 Nu[167] = 57.540001*

*MinusK[168] = 69.540001 PlusK[168] = -49.540001 Theta[168] = 10.000000 Nu[168] = 59.540001*

***Flow properties of Interior points on Characteristic line 14 are:***

*MinusK[170] = 53.540001 PlusK[170] = -53.540001 Theta[170] = 0.000000 Nu[170] = 53.540001*

*MinusK[171] = 57.540001 PlusK[171] = -53.540001 Theta[171] = 2.000000 Nu[171] = 55.540001*

*MinusK[172] = 61.540001 PlusK[172] = -53.540001 Theta[172] = 4.000000 Nu[172] = 57.540001*

*MinusK[173] = 65.540001 PlusK[173] = -53.540001 Theta[173] = 6.000000 Nu[173] = 59.540001*

*MinusK[174] = 69.540001 PlusK[174] = -53.540001 Theta[174] = 8.000000 Nu[174] = 61.540001*

***Flow properties of Interior points on Characteristic line 15 are:***

*MinusK[176] = 57.540001 PlusK[176] = -57.540001 Theta[176] = 0.000000 Nu[176] = 57.540001*

*MinusK[177] = 61.540001 PlusK[177] = -57.540001 Theta[177] = 2.000000 Nu[177] = 59.540001*

*MinusK[178] = 65.540001 PlusK[178] = -57.540001 Theta[178] = 4.000000 Nu[178] = 61.540001*

*MinusK[179] = 69.540001 PlusK[179] = -57.540001 Theta[179] = 6.000000 Nu[179] = 63.540001*

***Flow properties of Interior points on Characteristic line 16 are:***

*MinusK[181] = 61.540001 PlusK[181] = -61.540001 Theta[181] = 0.000000 Nu[181] = 61.540001*

*MinusK[182] = 65.540001 PlusK[182] = -61.540001 Theta[182] = 2.000000 Nu[182] = 63.540001*

*MinusK[183] = 69.540001 PlusK[183] = -61.540001 Theta[183] = 4.000000 Nu[183] = 65.540001*

***Flow properties of Interior points on Characteristic line 17 are:***

*MinusK[185] = 65.540001 PlusK[185] = -65.540001 Theta[185] = 0.000000 Nu[185] = 65.540001*

*MinusK[186] = 69.540001 PlusK[186] = -65.540001 Theta[186] = 2.000000 Nu[186] = 67.540001*

***Flow properties of Interior points on Characteristic line 18 are:***

*MinusK[188] = 69.540001 PlusK[188] = -69.540001 Theta[188] = 0.000000 Nu[188] = 69.54000*

***Flow properties of the points on the Nozzle Wall:***

*MinusK[19] = 69.540001 PlusK[19] = 0.000000 Theta[19] = 34.770000 Nu[19] = 34.770000*

*MinusK[37] = 69.540001 PlusK[37] = -5.540001 Theta[37] = 32.000000 Nu[37] = 37.540001*

*MinusK[54] = 69.540001 PlusK[54] = -9.540001 Theta[54] = 30.000000 Nu[54] = 39.540001*

*MinusK[70] = 69.540001 PlusK[70] = -13.540001 Theta[70] = 28.000000 Nu[70] = 41.540001*

*MinusK[85] = 69.540001 PlusK[85] = -17.540001 Theta[85] = 26.000000 Nu[85] = 43.540001*

*MinusK[99] = 69.540001 PlusK[99] = -21.540001 Theta[99] = 24.000000 Nu[99] = 45.540001*

*MinusK[112] = 69.540001 PlusK[112] = -25.540001 Theta[112] = 22.000000 Nu[112] = 47.540001*

*MinusK[124] = 69.540001 PlusK[124] = -29.540001 Theta[124] = 20.000000 Nu[124] = 49.540001*

*MinusK[135] = 69.540001 PlusK[135] = -33.540001 Theta[135] = 18.000000 Nu[135] = 51.540001*

*MinusK[145] = 69.540001 PlusK[145] = -37.540001 Theta[145] = 16.000000 Nu[145] = 53.540001*

*MinusK[154] = 69.540001 PlusK[154] = -41.540001 Theta[154] = 14.000000 Nu[154] = 55.540001*

*MinusK[162] = 69.540001 PlusK[162] = -45.540001 Theta[162] = 12.000000 Nu[162] = 57.540001*

*MinusK[169] = 69.540001 PlusK[169] = -49.540001 Theta[169] = 10.000000 Nu[169] = 59.540001*

*MinusK[175] = 69.540001 PlusK[175] = -53.540001 Theta[175] = 8.000000 Nu[175] = 61.540001*

*MinusK[180] = 69.540001 PlusK[180] = -57.540001 Theta[180] = 6.000000 Nu[180] = 63.540001*

*MinusK[184] = 69.540001 PlusK[184] = -61.540001 Theta[184] = 4.000000 Nu[184] = 65.540001*

*MinusK[187] = 69.540001 PlusK[187] = -65.540001 Theta[187] = 2.000000 Nu[187] = 67.540001*

*MinusK[189] = 69.540001 PlusK[189] = -69.540001 Theta[189] = 0.000000 Nu[189] = 69.540001*

## 5.2 Determination of Mach angle of all the points in the grid

A formula was used (ref. paper on Inverse Prandtl Meyer function [web links-[1]]) to determine the Mach number (M) using the Prandtl Meyer angle () [generated by the program], which in turn were used to find the Mach angle (μ).

The Prandtl Meyer function solved for M obtains a polynomial function for M:

i.e.,

Where, and

The constants are:

|  |  |
| --- | --- |
| A | 1.3604 |
| B | 0.0962 |
| C | -0.5127 |
| D | -0.6722 |
| E | -0.3278 |

After obtaining the Mach numbers, it was observed that, when compared to the Mach numbers in the table [2], the Mach numbers obtained from the formula had high degree of errors. It was also observed that the Mach numbers obtained had negative values for some Prandtl Meyer angles.

Example:

**Table 5.1: Calculation of Mach angle using the formula**

|  |  |  |
| --- | --- | --- |
| Prandtl Meyer angle | Mach number | Mach number (as per table) |
| 0.1257 | 1.337252519 | 1.02 |
| 0.351 | 1.778898899 | 1.04 |
| 0.6367 | 2.389299109 | 1.06 |
| 0.968 | 3.314231264 | 1.08 |
| 1.336 | 4.959525163 | 1.1 |
| 1.735 | 9.023375649 | 1.12 |
| 2.16 | 42.75166358 | 1.14 |
| 2.607 | -15.04813207 | 1.16 |
| 3.074 | -6.02902456 | 1.18 |
| 3.558 | -3.511071799 | 1.2 |
| 4.057 | -2.268889818 | 1.22 |
| 4.569 | -1.493766092 | 1.24 |
| 5.093 | -0.940583103 | 1.26 |
| 5.627 | -0.510996648 | 1.28 |
| 6.17 | -0.156997087 | 1.3 |
| 6.721 | 0.147262316 | 1.32 |
| 7.279 | 0.416900915 | 1.34 |
| 7.844 | 0.661740246 | 1.36 |
| 8.413 | 0.88706146 | 1.38 |

Thus the ‘Mach number and the Prandtl-Meyer angle calculator’ was used to obtain the Mach Numbers for the corresponding Prandtl Meyer angles.

The Mach angle was calculated using the undermentioned formula:

Where, M is the Mach number

µ is the Mach angle.

The values obtained are shown below:

**Table 5.2: Computation of Mach angle**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Points** |  | **Mach Number (M)** | **1/M** | **= sin -1(1/M) (rad)** | **(deg)=(rad)\*180)/** |
| 1 | 0.77 | 1.068345 | 0.936027 | 1.211166664 | 69.39 |
| 2 | 2.77 | 1.167056 | 0.856857 | 1.029141908 | 58.97 |
| 3 | 4.77 | 1.24771 | 0.801468 | 0.929746376 | 53.27 |
| 4 | 6.77 | 1.321753 | 0.756571 | 0.85805327 | 49.16 |
| 5 | 8.77 | 1.392456 | 0.718156 | 0.801148157 | 45.90 |
| 6 | 10.77 | 1.461349 | 0.684299 | 0.753642259 | 43.18 |
| 7 | 12.77 | 1.529318 | 0.653886 | 0.712709612 | 40.84 |
| 8 | 14.77 | 1.596945 | 0.626196 | 0.676664122 | 38.77 |
| 9 | 16.77 | 1.664652 | 0.600726 | 0.644409115 | 36.92 |
| 10 | 18.77 | 1.732766 | 0.577112 | 0.615187883 | 35.25 |
| 11 | 20.77 | 1.801554 | 0.555076 | 0.58845474 | 33.72 |
| 12 | 22.77 | 1.87125 | 0.534402 | 0.563800252 | 32.30 |
| 13 | 24.77 | 1.942061 | 0.514917 | 0.54091069 | 30.99 |
| 14 | 26.77 | 2.014184 | 0.496479 | 0.519537791 | 29.77 |
| 15 | 28.77 | 2.087804 | 0.478972 | 0.499483455 | 28.62 |
| 16 | 30.77 | 2.163107 | 0.462298 | 0.480584992 | 27.54 |
| 17 | 32.77 | 2.240275 | 0.446374 | 0.462708877 | 26.51 |
| 18 | 34.77 | 2.319498 | 0.431128 | 0.4457423 | 25.54 |
| 19 | 34.77 | 2.319498 | 0.431128 | 0.4457423 | 25.54 |
| 20 | 5.54 | 1.276758 | 0.783234 | 0.899850201 | 51.56 |
| 21 | 7.54 | 1.349265 | 0.741144 | 0.834773175 | 47.83 |
| 22 | 9.54 | 1.419136 | 0.704654 | 0.781935536 | 44.80 |
| 23 | 11.54 | 1.48759 | 0.672228 | 0.73721442 | 42.24 |
| 24 | 13.54 | 1.555369 | 0.642934 | 0.69832314 | 40.01 |
| 25 | 15.54 | 1.622984 | 0.616149 | 0.663843968 | 38.04 |
| 26 | 17.54 | 1.690812 | 0.591432 | 0.632833343 | 36.26 |
| 27 | 19.54 | 1.759156 | 0.568454 | 0.604625997 | 34.64 |
| 28 | 21.54 | 1.828268 | 0.546966 | 0.578735464 | 33.16 |
| 29 | 23.54 | 1.898369 | 0.526768 | 0.554793728 | 31.79 |
| 30 | 25.54 | 1.969663 | 0.507701 | 0.532514261 | 30.51 |
| 31 | 27.54 | 2.04234 | 0.489634 | 0.511670447 | 29.32 |
| 32 | 29.54 | 2.116587 | 0.472459 | 0.492078418 | 28.19 |
| 33 | 31.54 | 2.192586 | 0.456082 | 0.47358816 | 27.13 |
| 34 | 33.54 | 2.270522 | 0.440427 | 0.456074627 | 26.13 |
| 35 | 35.54 | 2.350587 | 0.425426 | 0.439432167 | 25.18 |
| 36 | 37.54 | 2.432978 | 0.411019 | 0.42357148 | 24.27 |
| 37 | 37.54 | 2.432978 | 0.411019 | 0.42357148 | 24.27 |
| 38 | 9.54 | 1.419136 | 0.704654 | 0.781935536 | 44.80 |
| 39 | 11.54 | 1.48759 | 0.672228 | 0.73721442 | 42.24 |
| 40 | 13.54 | 1.555369 | 0.642934 | 0.69832314 | 40.01 |
| 41 | 15.54 | 1.622984 | 0.616149 | 0.663843968 | 38.04 |
| 42 | 17.54 | 1.690812 | 0.591432 | 0.632833343 | 36.26 |
| 43 | 19.54 | 1.759156 | 0.568454 | 0.604625997 | 34.64 |
| 44 | 21.54 | 1.828268 | 0.546966 | 0.578735464 | 33.16 |
| 45 | 23.54 | 1.898369 | 0.526768 | 0.554793728 | 31.79 |
| 46 | 25.54 | 1.969663 | 0.507701 | 0.532514261 | 30.51 |
| 47 | 27.54 | 2.04234 | 0.489634 | 0.511670447 | 29.32 |
| 48 | 29.54 | 2.116587 | 0.472459 | 0.492078418 | 28.19 |
| 49 | 31.54 | 2.192586 | 0.456082 | 0.47358816 | 27.13 |
| 50 | 33.54 | 2.270522 | 0.440427 | 0.456074627 | 26.13 |
| 51 | 35.54 | 2.350587 | 0.425426 | 0.439432167 | 25.18 |
| 52 | 37.54 | 2.432978 | 0.411019 | 0.42357148 | 24.27 |
| 53 | 39.54 | 2.517902 | 0.397156 | 0.40841593 | 23.40 |
| 54 | 39.54 | 2.517902 | 0.397156 | 0.40841593 | 23.40 |
| 55 | 13.54 | 1.555369 | 0.642934 | 0.69832314 | 40.01 |
| 56 | 15.54 | 1.622984 | 0.616149 | 0.663843968 | 38.04 |
| 57 | 17.54 | 1.690812 | 0.591432 | 0.632833343 | 36.26 |
| 58 | 19.54 | 1.759156 | 0.568454 | 0.604625997 | 34.64 |
| 59 | 21.54 | 1.828268 | 0.546966 | 0.578735464 | 33.16 |
| 60 | 23.54 | 1.898369 | 0.526768 | 0.554793728 | 31.79 |
| 61 | 25.54 | 1.969663 | 0.507701 | 0.532514261 | 30.51 |
| 62 | 27.54 | 2.04234 | 0.489634 | 0.511670447 | 29.32 |
| 63 | 29.54 | 2.116587 | 0.472459 | 0.492078418 | 28.19 |
| 64 | 31.54 | 2.192586 | 0.456082 | 0.47358816 | 27.13 |
| 65 | 33.54 | 2.270522 | 0.440427 | 0.456074627 | 26.13 |
| 66 | 35.54 | 2.350587 | 0.425426 | 0.439432167 | 25.18 |
| 67 | 37.54 | 2.432978 | 0.411019 | 0.42357148 | 24.27 |
| 68 | 39.54 | 2.517902 | 0.397156 | 0.40841593 | 23.40 |
| 69 | 41.54 | 2.605577 | 0.383792 | 0.393899448 | 22.57 |
| 70 | 41.54 | 2.605577 | 0.383792 | 0.393899448 | 22.57 |
| 71 | 17.54 | 1.690812 | 0.591432 | 0.632833343 | 36.26 |
| 72 | 19.54 | 1.759156 | 0.568454 | 0.604625997 | 34.64 |
| 73 | 21.54 | 1.828268 | 0.546966 | 0.578735464 | 33.16 |
| 74 | 23.54 | 1.898369 | 0.526768 | 0.554793728 | 31.79 |
| 75 | 25.54 | 1.969663 | 0.507701 | 0.532514261 | 30.51 |
| 76 | 27.54 | 2.04234 | 0.489634 | 0.511670447 | 29.32 |
| 77 | 29.54 | 2.116587 | 0.472459 | 0.492078418 | 28.19 |
| 78 | 31.54 | 2.192586 | 0.456082 | 0.47358816 | 27.13 |
| 79 | 33.54 | 2.270522 | 0.440427 | 0.456074627 | 26.13 |
| 80 | 35.54 | 2.350587 | 0.425426 | 0.439432167 | 25.18 |
| 81 | 37.54 | 2.432978 | 0.411019 | 0.42357148 | 24.27 |
| 82 | 39.54 | 2.517902 | 0.397156 | 0.40841593 | 23.40 |
| 83 | 41.54 | 2.605577 | 0.383792 | 0.393899448 | 22.57 |
| 84 | 43.54 | 2.696239 | 0.370887 | 0.379963962 | 21.77 |
| 85 | 43.54 | 2.696239 | 0.370887 | 0.379963962 | 21.77 |
| 86 | 21.54 | 1.828268 | 0.546966 | 0.578735464 | 33.16 |
| 87 | 23.54 | 1.898369 | 0.526768 | 0.554793728 | 31.79 |
| 88 | 25.54 | 1.969663 | 0.507701 | 0.532514261 | 30.51 |
| 89 | 27.54 | 2.04234 | 0.489634 | 0.511670447 | 29.32 |
| 90 | 29.54 | 2.116587 | 0.472459 | 0.492078418 | 28.19 |
| 91 | 31.54 | 2.192586 | 0.456082 | 0.47358816 | 27.13 |
| 92 | 33.54 | 2.270522 | 0.440427 | 0.456074627 | 26.13 |
| 93 | 35.54 | 2.350587 | 0.425426 | 0.439432167 | 25.18 |
| 94 | 37.54 | 2.432978 | 0.411019 | 0.42357148 | 24.27 |
| 95 | 39.54 | 2.517902 | 0.397156 | 0.40841593 | 23.40 |
| 96 | 41.54 | 2.605577 | 0.383792 | 0.393899448 | 22.57 |
| 97 | 43.54 | 2.696239 | 0.370887 | 0.379963962 | 21.77 |
| 98 | 45.54 | 2.790139 | 0.358405 | 0.366558919 | 21.00 |
| 99 | 45.54 | 2.790139 | 0.358405 | 0.366558919 | 21.00 |
| 100 | 25.54 | 1.969663 | 0.507701 | 0.532514261 | 30.51 |
| 101 | 27.54 | 2.04234 | 0.489634 | 0.511670447 | 29.32 |
| 102 | 29.54 | 2.116587 | 0.472459 | 0.492078418 | 28.19 |
| 103 | 31.54 | 2.192586 | 0.456082 | 0.47358816 | 27.13 |
| 104 | 33.54 | 2.270522 | 0.440427 | 0.456074627 | 26.13 |
| 105 | 35.54 | 2.350587 | 0.425426 | 0.439432167 | 25.18 |
| 106 | 37.54 | 2.432978 | 0.411019 | 0.42357148 | 24.27 |
| 107 | 39.54 | 2.517902 | 0.397156 | 0.40841593 | 23.40 |
| 108 | 41.54 | 2.605577 | 0.383792 | 0.393899448 | 22.57 |
| 109 | 43.54 | 2.696239 | 0.370887 | 0.379963962 | 21.77 |
| 110 | 45.54 | 2.790139 | 0.358405 | 0.366558919 | 21.00 |
| 111 | 47.54 | 2.887547 | 0.346315 | 0.353639855 | 20.26 |
| 112 | 47.54 | 2.887547 | 0.346315 | 0.353639855 | 20.26 |
| 113 | 29.54 | 2.116587 | 0.472459 | 0.492078418 | 28.19 |
| 114 | 31.54 | 2.192586 | 0.456082 | 0.47358816 | 27.13 |
| 115 | 33.54 | 2.270522 | 0.440427 | 0.456074627 | 26.13 |
| 116 | 35.54 | 2.350587 | 0.425426 | 0.439432167 | 25.18 |
| 117 | 37.54 | 2.432978 | 0.411019 | 0.42357148 | 24.27 |
| 118 | 39.54 | 2.517902 | 0.397156 | 0.40841593 | 23.40 |
| 119 | 41.54 | 2.605577 | 0.383792 | 0.393899448 | 22.57 |
| 120 | 43.54 | 2.696239 | 0.370887 | 0.379963962 | 21.77 |
| 121 | 45.54 | 2.790139 | 0.358405 | 0.366558919 | 21.00 |
| 122 | 47.54 | 2.887547 | 0.346315 | 0.353639855 | 20.26 |
| 123 | 49.54 | 2.988758 | 0.334587 | 0.341167088 | 19.55 |
| 124 | 49.54 | 2.988758 | 0.334587 | 0.341167088 | 19.55 |
| 125 | 33.54 | 2.270522 | 0.440427 | 0.456074627 | 26.13 |
| 126 | 35.54 | 2.350587 | 0.425426 | 0.439432167 | 25.18 |
| 127 | 37.54 | 2.432978 | 0.411019 | 0.42357148 | 24.27 |
| 128 | 39.54 | 2.517902 | 0.397156 | 0.40841593 | 23.40 |
| 129 | 41.54 | 2.605577 | 0.383792 | 0.393899448 | 22.57 |
| 130 | 43.54 | 2.696239 | 0.370887 | 0.379963962 | 21.77 |
| 131 | 45.54 | 2.790139 | 0.358405 | 0.366558919 | 21.00 |
| 132 | 47.54 | 2.887547 | 0.346315 | 0.353639855 | 20.26 |
| 133 | 49.54 | 2.988758 | 0.334587 | 0.341167088 | 19.55 |
| 134 | 51.54 | 3.094093 | 0.323196 | 0.329105317 | 18.86 |
| 135 | 51.54 | 3.094093 | 0.323196 | 0.329105317 | 18.86 |
| 136 | 37.54 | 2.432978 | 0.411019 | 0.42357148 | 24.27 |
| 137 | 39.54 | 2.517902 | 0.397156 | 0.40841593 | 23.40 |
| 138 | 41.54 | 2.605577 | 0.383792 | 0.393899448 | 22.57 |
| 139 | 43.54 | 2.696239 | 0.370887 | 0.379963962 | 21.77 |
| 140 | 45.54 | 2.790139 | 0.358405 | 0.366558919 | 21.00 |
| 141 | 47.54 | 2.887547 | 0.346315 | 0.353639855 | 20.26 |
| 142 | 49.54 | 2.988758 | 0.334587 | 0.341167088 | 19.55 |
| 143 | 51.54 | 3.094093 | 0.323196 | 0.329105317 | 18.86 |
| 144 | 53.54 | 3.203904 | 0.312119 | 0.317422869 | 18.19 |
| 145 | 53.54 | 3.203904 | 0.312119 | 0.317422869 | 18.19 |
| 146 | 41.54 | 2.605577 | 0.383792 | 0.393899448 | 22.57 |
| 147 | 43.54 | 2.696239 | 0.370887 | 0.379963962 | 21.77 |
| 148 | 45.54 | 2.790139 | 0.358405 | 0.366558919 | 21.00 |
| 149 | 47.54 | 2.887547 | 0.346315 | 0.353639855 | 20.26 |
| 150 | 49.54 | 2.988758 | 0.334587 | 0.341167088 | 19.55 |
| 151 | 51.54 | 3.094093 | 0.323196 | 0.329105317 | 18.86 |
| 152 | 53.54 | 3.203904 | 0.312119 | 0.317422869 | 18.19 |
| 153 | 55.54 | 3.318576 | 0.301334 | 0.306091443 | 17.54 |
| 154 | 55.54 | 3.318576 | 0.301334 | 0.306091443 | 17.54 |
| 155 | 45.54 | 2.790139 | 0.358405 | 0.366558919 | 21.00 |
| 156 | 47.54 | 2.887547 | 0.346315 | 0.353639855 | 20.26 |
| 157 | 49.54 | 2.988758 | 0.334587 | 0.341167088 | 19.55 |
| 158 | 51.54 | 3.094093 | 0.323196 | 0.329105317 | 18.86 |
| 159 | 53.54 | 3.203904 | 0.312119 | 0.317422869 | 18.19 |
| 160 | 55.54 | 3.318576 | 0.301334 | 0.306091443 | 17.54 |
| 161 | 57.54 | 3.438535 | 0.290822 | 0.295085366 | 16.91 |
| 162 | 57.54 | 3.438535 | 0.290822 | 0.295085366 | 16.91 |
| 163 | 49.54 | 2.988758 | 0.334587 | 0.341167088 | 19.55 |
| 164 | 51.54 | 3.094093 | 0.323196 | 0.329105317 | 18.86 |
| 165 | 53.54 | 3.203904 | 0.312119 | 0.317422869 | 18.19 |
| 166 | 55.54 | 3.318576 | 0.301334 | 0.306091443 | 17.54 |
| 167 | 57.54 | 3.438535 | 0.290822 | 0.295085366 | 16.91 |
| 168 | 59.54 | 3.564254 | 0.280564 | 0.284381262 | 16.29 |
| 169 | 59.54 | 3.564254 | 0.280564 | 0.284381262 | 16.29 |
| 170 | 53.54 | 3.203904 | 0.312119 | 0.317422869 | 18.19 |
| 171 | 55.54 | 3.318576 | 0.301334 | 0.306091443 | 17.54 |
| 172 | 57.54 | 3.438535 | 0.290822 | 0.295085366 | 16.91 |
| 173 | 59.54 | 3.564254 | 0.280564 | 0.284381262 | 16.29 |
| 174 | 61.54 | 3.696257 | 0.270544 | 0.273958016 | 15.70 |
| 175 | 61.54 | 3.696257 | 0.270544 | 0.273958016 | 15.70 |
| 176 | 57.54 | 3.438535 | 0.290822 | 0.295085366 | 16.91 |
| 177 | 59.54 | 3.564254 | 0.280564 | 0.284381262 | 16.29 |
| 178 | 61.54 | 3.696257 | 0.270544 | 0.273958016 | 15.70 |
| 179 | 63.54 | 3.835129 | 0.260747 | 0.263796326 | 15.11 |
| 180 | 63.54 | 3.835129 | 0.260747 | 0.263796326 | 15.11 |
| 181 | 61.54 | 3.696257 | 0.270544 | 0.273958016 | 15.70 |
| 182 | 63.54 | 3.835129 | 0.260747 | 0.263796326 | 15.11 |
| 183 | 65.54 | 3.981527 | 0.25116 | 0.2538784 | 14.55 |
| 184 | 65.54 | 3.981527 | 0.25116 | 0.2538784 | 14.55 |
| 185 | 65.54 | 3.981527 | 0.25116 | 0.2538784 | 14.55 |
| 186 | 67.54 | 4.136189 | 0.241768 | 0.244187954 | 13.99 |
| 187 | 67.54 | 4.136189 | 0.241768 | 0.244187954 | 13.99 |
| 188 | 69.54 | 4.299947 | 0.232561 | 0.234710061 | 13.45 |
| 189 | 69.54 | 4.299947 | 0.232561 | 0.234710061 | 13.45 |

## 5.3 Determination of the co-ordinates of points on the axis line

The coordinates of a point ( can be determined using the formula below:

But, the values of x1, y1, x2, y2 were unknown.

Hence, trigonometric relations were used to calculate the co-ordinates of points on the axis line.

### 5.3.1 Determination of coordinates of points on the axis line using trigonometric relations

A

ᶿ

Y

C

B

X

Fig 5.1: Determination of axis coordinates through trigonometery

Consider ΔABC,

Where,

Y = the vertical distance.

X = the distance from the origin.

= the angle between the vertical line and the characteristic line.

The general formula is,

Therefore, the distance from the origin i.e., X and co-ordinates (x, 0) for the respective points were obtained.

Example:

Consider the axis point 1 on the axis line.

Y= 33.54mm

X = 33.54\* tan (0.77)

X = 0.45mm

Therefore, the co-ordinate for above stated point on the axis line is (0.45, 0).

Similarly, the co-ordinates for all the points on the axis line were calculated and the values are given below in the table.

**Table 5.3: Determination of axis point coordinates**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Axis points** |  |  | **(radians)** |  | **Vertical length** | **Distance from origin** |
| 1 | 0.77 | 2.419026343 | 0.013439035 | 0.013439844 | 33.54 | 0.45 |
| 20 | 2.77 | 8.70221165 | 0.04834562 | 0.048383322 | 33.54 | 1.62 |
| 38 | 4.77 | 14.98539696 | 0.083252205 | 0.083445078 | 33.54 | 2.80 |
| 55 | 6.77 | 21.26858226 | 0.11815879 | 0.11871177 | 33.54 | 3.98 |
| 71 | 8.77 | 27.55176757 | 0.153065375 | 0.154272075 | 33.54 | 5.17 |
| 86 | 10.77 | 33.83495288 | 0.18797196 | 0.190217604 | 33.54 | 6.38 |
| 100 | 12.77 | 40.11813819 | 0.222878545 | 0.226643866 | 33.54 | 7.60 |
| 113 | 14.77 | 46.40132349 | 0.257785131 | 0.263651324 | 33.54 | 8.84 |
| 125 | 16.77 | 52.6845088 | 0.292691716 | 0.301346564 | 33.54 | 10.11 |
| 136 | 18.77 | 58.96769411 | 0.327598301 | 0.339843593 | 33.54 | 11.40 |
| 146 | 20.77 | 65.25087942 | 0.362504886 | 0.379265332 | 33.54 | 12.72 |
| 155 | 22.77 | 71.53406472 | 0.397411471 | 0.419745308 | 33.54 | 14.08 |
| 163 | 24.77 | 77.81725003 | 0.432318056 | 0.461429634 | 33.54 | 15.48 |
| 170 | 26.77 | 84.10043534 | 0.467224641 | 0.50447932 | 33.54 | 16.92 |
| 176 | 28.77 | 90.38362064 | 0.502131226 | 0.549073002 | 33.54 | 18.42 |
| 181 | 30.77 | 96.66680595 | 0.537037811 | 0.595410198 | 33.54 | 19.97 |
| 185 | 32.77 | 102.9499913 | 0.571944396 | 0.643715211 | 33.54 | 21.59 |
| 188 | 34.77 | 109.2331766 | 0.606850981 | 0.694241865 | 33.54 | 23.28 |

## 5.4 Construction of nozzle profile using Solid Edge

### 5.4.1 Ideal contour nozzle

Using the values obtained in the table, two designs of ideal contour nozzle were made

1. An approximate design
2. An actual design

**Procedure for approximate design:**

1. Construct the nozzle throat (radius = 33.54mm) and an arc (radius = 0.5 times the throat radius, sweep angle = 23.9 deg).
2. Using the axis line point coordinates construct the axis line and then using the angles between the right characteristic lines,construct the right characteristic lines.
3. Construct the left running characteristic lines using the value of Mach angle at the axis line points.
4. From the end of the arc, take an average of θ between each of the wall points and obtain a curve.
5. Extend the left running characteristic lines to cut the curves from the wall points so as to obtain the nozzle profile.

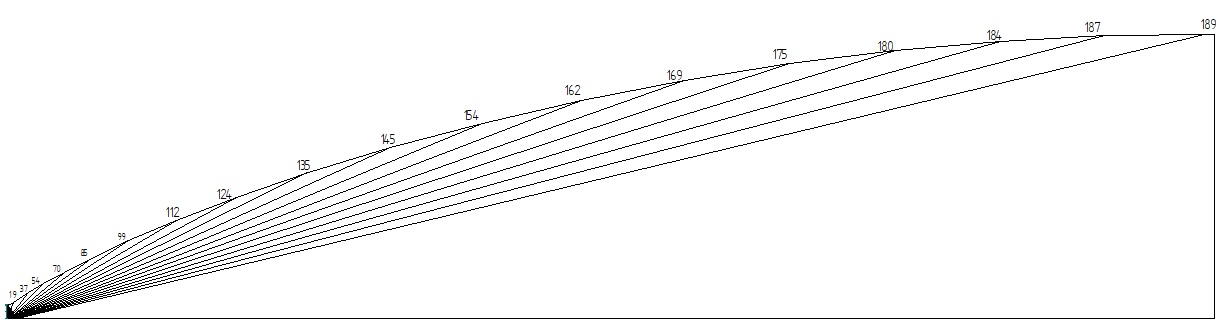
**Approximate design:**

Fig 5.2: Approximate design of Ideal contour nozzle

**At the throat:**

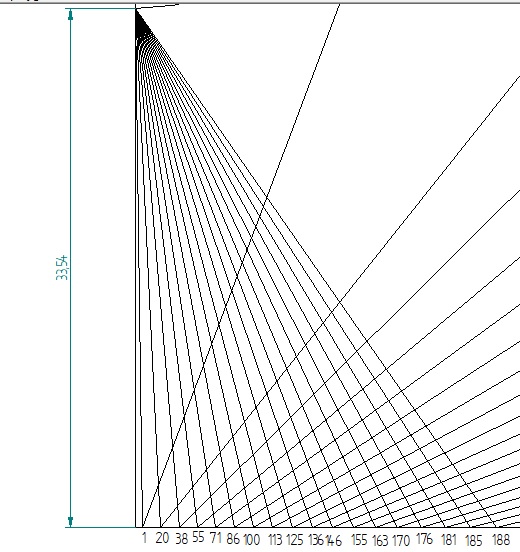


Fig. 5.3: Left and right running characteristics at the throat of approximate design

The specifications of the approximate nozzle design are:

Length of the nozzle = 3013.14 mm

Nozzle exit radius = 709.88 mm

Area ratio of the nozzle = 21.165

Downstream wall radius = 0.5\*33.54 = 16.77mm

**Procedure for actual design:**

1. Construct the nozzle throat (radius =33.54mm) and an arc (radius= 0.5 times the throat radius, sweep angle = 23.9 deg).
2. Using the axis line point coordinates construct the axis line and then using the angles between the right characteristic lines, construct the right characteristic lines.
3. Construct the left running characteristic lines using the value of μ+θ at each point on the left running characteristics (refer table 5.2 for values of μ and θ).
4. From the end of the arc, take an average of θ between each of the wall points and obtain a curve.
5. Extend the left running characteristic lines to cut the curves from the wall points so as to obtain the nozzle profile.

**Actual design:**

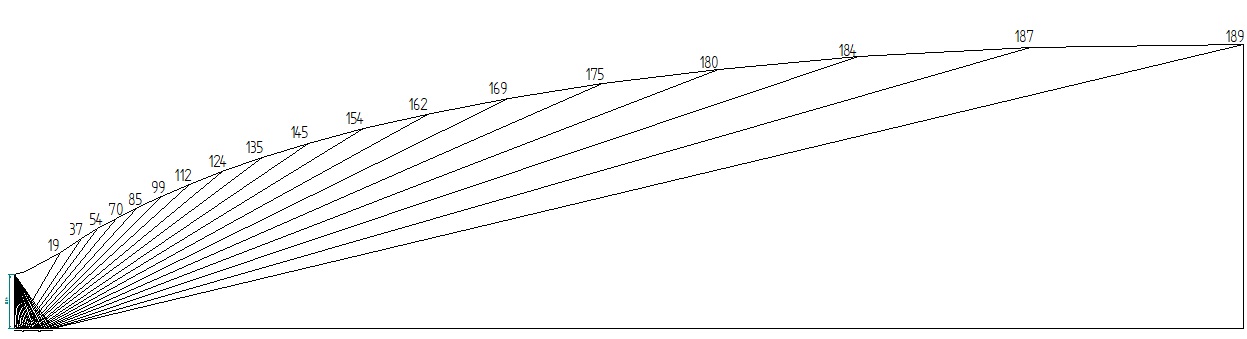


Fig 5.4: Actual design of Ideal contour nozzle

**At the throat:**

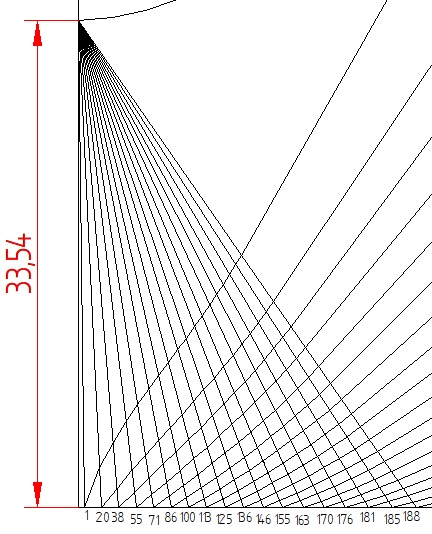


Fig. 5.5: Left and right running characteristics at the throat of actual design

The specifications of the actual nozzle design are:

Length of the nozzle = 751.84mm

Nozzle exit radius = 174.24mm

Area ratio of the nozzle = 5.195

Downstream wall radius = 0.5\*33.54 = 16.77mm

### 4.4.2 Truncated Ideal Contour Nozzle (TIC)

If the nozzle is truncated at 82.5% of its length, the design and nozzle specifications are as follows:

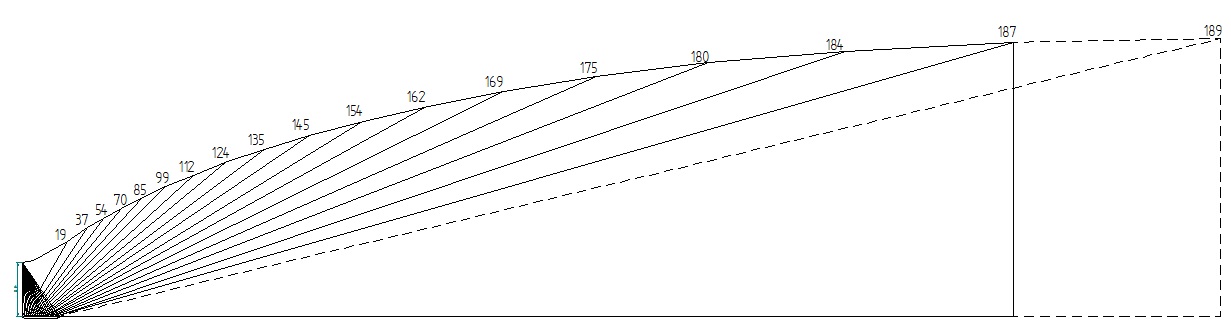


Fig 5.6: Truncated Ideal contour nozzle

The specifications of the truncated nozzle design are:

Length of the nozzle = 621.185mm

Nozzle exit radius = 171.97

Area ratio of the nozzle = 5.127

Downstream wall radius = 0.5\*33.54 = 16.77mm

## 5.5 Actual design Vs. Approximate design

**Table 5.4:**

|  |  |  |
| --- | --- | --- |
| **Nozzle specifications** | **Approximate design** | **Actual design** |
| Nozzle throat radius | 33.54mm | 33.54mm |
| Nozzle exit radius | 709.88 mm | 171.97mm |
| Area Ratio | 21.165 | 5.195 |
| Nozzle Length | 3013.14 mm | 751.84mm |
| Throat downstream wall radius | 0.5 | 0.5 |
| Throat wall angle | 23.9˚ | 23.9˚ |
| Design Mach number | 4.3 | 4.3 |

# CONCLUSION

A Truncated Ideal Contour nozzle was successfully designed using the Method of Characteristics. Flow properties at all the grid points in the nozzle geometry were obtained by C Programming and the co-ordinates were obtained using trigonometric relations and the modelling software, Solid Edge. The resulting design is different from the actual design which was taken as the reference nozzle.

It was learnt that the errors can be eliminated by incorporating boundary layer corrections while designing the nozzle and with a polynomial curve in the initial expansion region just downstream of the throat.

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**Website Links**

[1]. [www.pdas.com/pm.pdf](http://www.pdas.com/pm.pdf) - Inverse Prandtl Meyer Function   
[2]. [www.atkinsonscience.co.uk/Webapps/PrandtlMeyerFunction.aspx](http://www.atkinsonscience.co.uk/Webapps/PrandtlMeyerFunction.aspx) - Prandtl Meyer Angle – Mach number Calculator