

Design and Analysis of Minimum length Nozzle by using MAT lab coding

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ABSTRACT

This research work aims to analyze the Minimum Length Nozzle. In this paper, Numerical analysis (finite element analysis, FEA) has been carried out by developing programming in mathematical software MATLAB and the results obtained from MATLAB are giving good agreement with the results obtained by classical method - exact solutions. Later, for the same structure, analysis has been carried out using finite element analysis software ANSYS. This job is helpful for obtaining the results not only at node points but also the entire surface of the Minimum Length Nozzle. Finally, comparison has been done between the results obtained from FEA numerical analysis, and ANSYS results with classical method - exact solutions. Numerical results showed that, the results obtained by finite element analysis and ANSYS simulation results are in close agreement with the results obtained from exact solutions from classical method. During this analysis to show the accurate and exact Shape of the nozzle with exact solutions.

1. INTRODUCTION TO NOZZLE

A Nozzle is a device designed to control the direction or characteristics of a fluid flow (especially to increase velocity) as it exits (or enters) an enclosed chamber or pipe. A nozzle is often a pipe or tube of varying cross sectional area and it can be used to direct or modify the flow of a fluid (liquid or gas). Nozzles are frequently used to control the rate of flow, speed, direction, mass, shape, and the pressure of the stream that emerges from them.



FIG: NOZZLE

Frequently, the goal is to increase the kinetic energy of the flowing medium at the expense of its pressure and internal energy. Nozzles can be described as convergent (narrowing down from a wide diameter to a smaller diameter in the direction of the flow) or divergent (expanding from a smaller diameter to a larger one). A de Laval nozzle has a convergent section followed by a divergent section and is often called a convergent-divergent nozzle ("con-di nozzle"). Convergent nozzles accelerate subsonic fluids. If the nozzle pressure ratio is high enough, then the flow will reach sonic velocity at the narrowest point (i.e. the nozzle throat). In this situation, the nozzle is said to be choked.

Increasing the nozzle pressure ratio further will not increase the throat Mach number above one. Downstream (i.e. external to the nozzle) the flow is free to expand to supersonic velocities however Mach 1 can be a very high speed for a hot gas because the speed of sound varies as the square root of absolute temperature. This fact is used extensively in rocketry where hypersonic flows are required and where propellant mixtures are deliberately chosen to further increase the sonic speed. Divergent nozzles slow fluids if the flow is subsonic, but they accelerate sonic or supersonic fluids.

Convergent-divergent nozzles can therefore accelerate fluids that have choked in the convergent section to supersonic speeds. This C-D process is more efficient than allowing a convergent nozzle to expand supersonically externally. The shape of the divergent section also ensures that the direction of the escaping gases is directly backwards, as any sideways component would not contribute to thrust.

2. LITERATURE SURVEY

BACKGROUND AND HISTORY:

Finite element analysis (FEA) is a powerful computational technique used for solving engineering problems having complex geometries that are subjected to general boundary conditions. While the analysis is being carried out, the field variables are varied from point to point, thus, possessing an infinite number of solutions in the domain. So, the

problem is quite complex. To overcome this difficulty FEA is used; the system is discretized into a finite number of parts known as elements by expressing the unknown field variable in terms of the assumed approximating functions within each element. For each element, systematic approximate solution is constructed by applying the variational or weighted residual methods. These functions (also called interpolation functions) are, included in terms of field variables at specific points referred to as nodes. Nodes are usually located along the element boundaries, and they connect adjacent elements. Because of its flexibility in ability to discretized the irregular domains with finite elements, this method has been used as a practical analysis tool for solving problems in various engineering disciplines. FEA is used in new product design, and existing product refinement. Because of its characteristics, researchers are able to verify a proposed design to the user's specifications before manufacturing or construction. In case of structural failure, FEA may be used to determine the design modifications to meet the required conditions. Structural analysis consists of linear and non-linear models. Linear models consider simple parameters and assume that the material is not plastically deformed. Non-linear models consider that the structure is pre-stressed and is plastically deformed.

Generally three types of analysis are used in FEA:

1. 1-D modelling is useful for solving beam, bar and truss elements
2. 2-D modelling is useful for solving plane stress and plane strain problems and
3. 3-D modelling is useful for solving complex solid structures.

In the earlier period, some of the researchers have been dealt exact solutions of plate deflections with different boundary conditions. Bhattacharya (1986) investigated the deflection of plates under static and dynamic loads by using a new finite difference analysis. This approach gives the forth order bi-harmonic equation which varies from node to node and found the true mode shape of the plate at each node. Defu and sheikh (2005) have presented the mathematical approach for large deflection of rectangular plates. Their analysis, based on the two forth order and second degree partial differential Von karman equations, found lateral deflection to applied load. This solution can be used to direct practical analysis of plates with different boundary conditions. Bakker et al. (2008) have studied the approximate analysis method for large deflection of rectangular thin plate with simply supported boundary condition under action of transverse loads. This approach gives the shape of initial and total deflection of plates. From this analysis, the large deflection behaviour of plate under transverse load can be expressed as a function of the pre to post buckling in-plane stiffness of plate. Liew et al. (2001) developed the differential quadrature method and harmonic differential quadrature method for static analysis of three dimensional rectangular plates. This methodology can be used to found the bending and buckling of plates, which are simply supported and clamped boundary conditions only. In the past, some researchers utilized FEA in solving problem plates with holes. Jain (2009) recently analyzed the effect of D/A ratio (where D is hole diameter and A is plate width) upon stress concentration factor and deflection in isotropic and orthotropic plates under transverse static loading. Chaudhuri

(1987) presented a theory for stress analysis by using rhombic array of alternating method for multiple circular holes. He worked on effects of stress concentration on a laminated plate with hole by finite element method. Paul and Rao (1989) presented a theory for evaluation of stress concentration factor of thick and FRP laminated plate with the help of Lo-Christensen-Wu higher order bending theory under transverse loading. In the last few decades, authors have considered plates with stiffener. Although the stiffened rectangular plates have been thoroughly studied, the application of stiffeners to circular plates is not so popular. Steen and Byklum (2004) presented an analysis for reducing deflection in isotropic circular plates under the action of static pressure by considering two stiffening rings. In their methodology, they conducted clamped edge boundary conditions throughout the analysis. Troipsky (1976) carried out his work for stiffened plates under bending, stability and vibration. Pape and Fox (2006) presented an infinite series approach for verity of plate aspect ratio by using stiffened elastic beam. For smoothen the elements, Xuan et al. (2007) have used boundary integral method. Das et al. (2009) have developed a quite general method which can be applied to any classical boundary conditions. Jain (2009) presented analysis of stress concentration and deflection in isotropic and orthotropic rectangular plates with central circular hole under transverse static loading. He considered three types of elements to solve square plate problems with various boundary conditions and loadings. Shaiov and Vorus (1986) developed an integral equation formulation for an Elasto-plastic plate bending. This technique is used for finding plasticity characteristics as well as the external lateral loading. Paiva and Aliabadi (2004) presented a formulation for the analysis of Kirchhoff plates with sub-regions by varying the thickness for boundary element method. This can be used for analyzing building floors such that the boundary integral equations of curvatures of points located at the zone's interfaces are deduced in a very easy way that makes it possible to get the bending moments. The present work deals with the analysis of an isotropic rectangular element being considered as a plane stress condition. This paper deals with FEA of isotropic rectangular plates under various boundary conditions and loadings. Throughout the analysis, the master element which is four noded quadrilateral elements, are used. Later, experiments have been conducted for same, using ANSYS. Finally, results have been checked with exact results obtained from Method of characteristics (MOC).

3. THEORITICAL BACKGROUND

INTRODUCTION TO METHOD OF CHARACTERISTICS

The method of characteristics has been used for many years to compute supersonic irrotational flows. Although the method has a strong analytical basis, its practical implementation is, essentially, always numerical and it is then used to compute the values of the flow variables at a series of distinct points in the flow rather than continuously throughout the flow field.

Let's consider a general steady two-dimensional irrotational flow field. We have already derived the velocity potential (ϕ) equation for such flow field.

$$\left(1 - \frac{u^2}{a^2}\right) \frac{\partial^2 \phi}{\partial x^2} + \left(1 - \frac{v^2}{a^2}\right) \frac{\partial^2 \phi}{\partial y^2} - \frac{2uv}{a^2} \frac{\partial^2 \phi}{\partial x \partial y} = 0 \quad \text{----- (3.1)}$$

Consider the change in any flow variable, f , df which can be determined by small changes in the coordinates dx and dy as illustrated in Fig.1.2. The change in the variable, df ,

$$df = \frac{\partial f}{\partial x} dx + \frac{\partial f}{\partial y} dy$$

If $f = \frac{\partial \phi}{\partial x}$ then this will give:

$$d\left(\frac{\partial \phi}{\partial x}\right) = \frac{\partial^2 \phi}{\partial x^2} dx + \frac{\partial^2 \phi}{\partial x \partial y} dy$$

But $u = \frac{\partial \phi}{\partial y}$ so this equation gives:

$$du = \frac{\partial^2 \phi}{\partial x^2} dx + \frac{\partial^2 \phi}{\partial x \partial y} dy \quad \text{----- (3.2)}$$

Similarly if $f = \frac{\partial \phi}{\partial y}$ then this will give:

$$d\left(\frac{\partial \phi}{\partial y}\right) = \frac{\partial^2 \phi}{\partial x \partial y} dx + \frac{\partial^2 \phi}{\partial y^2} dy$$

But $v = \frac{\partial \phi}{\partial x}$ so this equation gives:

$$dv = \frac{\partial^2 \phi}{\partial x \partial y} dx + \frac{\partial^2 \phi}{\partial y^2} dy \quad \text{----- (3.3)}$$

Now consider eqs. 3.1, 3.2 and 3.3 which involve second derivatives of ϕ and can be solved using Cramer's Rule.

For example

$$\frac{\partial^2 \phi}{\partial x \partial y} = \frac{(1 - u^2/a^2)dudy + (1 - v^2/a^2)dvdx}{(1 - u^2/a^2)(dy)^2 + (2uv/a^2)dxdy + (1 - v^2/a^2)(dx)^2} \quad \text{----- (3.4)}$$

In general, this equation can be solved for any chosen values of dx and dy, i.e., for any chosen direction, to give $\frac{\partial^2 \phi}{\partial x \partial y}$ at a selected point in the flow. However, it is possible to have $\frac{\partial^2 \phi}{\partial x \partial y}$ indeterminate in certain directions. Moreover this differential is expected to be finite at that point. Hence in these directions, eq. 32.4 must give an indeterminate value.

$$\frac{\partial^2 \phi}{\partial x \partial y} = \frac{0}{0}$$

Let's consider the denominator of eq 32.4 since along a particular direction $\frac{\partial^2 \phi}{\partial x \partial y}$ is indeterminate. Hence the denominator should be zero, as:

$$\left(1 - \frac{u^2}{a^2}\right)(dy)^2 + \frac{2uv}{a^2} dx dy + \left(1 - \frac{v^2}{a^2}\right)(dx)^2 = 0$$

Dividing by $(dx)^2$ gives:

$$\left(1 - \frac{u^2}{a^2}\right)\left(\frac{dy}{dx}\right)^2 + \frac{2uv}{a^2} \frac{dy}{dx} + \left(1 - \frac{v^2}{a^2}\right) = 0$$

The subscript 'ch' on dy/dx indicates that the slope of the characteristic line or a specific direction is being considered along which differentials are indeterminate. Solving above equation we get:

$$\left(\frac{dy}{dx}\right)_{ch} = \frac{-\left(\frac{uv}{a^2}\right) \pm \sqrt{\left(\frac{uv}{a^2}\right)^2 - \left(1 - \frac{u^2}{a^2}\right)\left(1 - \frac{v^2}{a^2}\right)}}{\left(1 - \frac{u^2}{a^2}\right)}$$

Let's represent the component of velocities in terms of velocity vector and angle made by the streamline with co-ordinate axes as,

$$V^2 = u^2 + v^2$$

$$u = V \cos \theta$$

$$v = V \sin \theta$$

Hence, we get the same equation for slope as,

$$\left(\frac{dy}{dx}\right)_{ch} = \frac{-M^2 \cos \theta \sin \theta \pm \sqrt{M^2 - 1}}{(1 - M^2 \cos^2 \theta)}$$

Where, $M=V/a$.

We can introduce the local Mach angle, α , where ($M = 1 / \sin \alpha$, $\sqrt{M^2 - 1} = 1 / \tan \alpha$) by replacing Mach number as,

$$\left(\frac{dy}{dx}\right)_{ch} = \frac{\cos \theta \sin \theta \pm \cos \alpha \sin \alpha}{\sin^2 \alpha - \cos^2 \alpha}$$

After much manipulation and rearrangement, it can be shown that this equation gives:

$$\left(\frac{dy}{dx}\right)_{ch} = \tan(\theta \pm \alpha) \quad \text{----- (3.5)}$$

There are two characteristic lines. This clearly means that the characteristic lines or lines along which derivatives are indeterminate makes Mach angle with the streamline. Hence the net angle made by the characteristic line with the x-axis is the summation of the angle made by the streamline with x-axis and angle made by the Mach wave with streamline. Hence Mach waves are the characteristic lines.

4. DESIGN OF GRADUAL EXPANSION NOZZLE

The steps involved in this calculation are precisely same as those used for the minimum length nozzle except for the fact that the expansion fan at the sharp corner is now replaced by a series of right running characteristic lines originating from the arc of the circle. One major assumption that has been made here is that a characteristic originating from any point on the expansion section is always reflected from the axis in such a way that it reaches the straightening portion of the nozzle. Multiple reflections of characteristic lines within the smooth expansion portion of the nozzle would make the problem much complicated without really improving the results much.

5. MATLAB COMPUTING AND ANALYSIS

MATLAB¹ is commercial software and a trademark of The Math Works, Inc., USA. It is an integrated programming system, including graphical interfaces and a large number of specialized toolboxes. MATLAB is getting increasingly popular in all fields of science and engineering. A Windows version of MATLAB is assumed here. The syntax is very similar for the DOS version. MATLAB integrates mathematical computing, visualization, and a

powerful language to provide a flexible environment for technical computing. The open architecture makes it easy to use MATLAB and its companion products to explore data, create algorithms and create custom tools that provide early insights and competitive advantages.

Known for its highly optimized matrix and vector calculations, MATLAB offers an intuitive language for expressing problems and their solutions both mathematically and visually. Typical uses include:

- Numeric computation and algorithm development.
- Symbolic computation (with the built-in Symbolic Math functions).
- Modeling, simulation and prototyping.
- Data analysis and signal processing.
- Engineering graphics and scientific visualization.

To start MATLAB click on the MATLAB icon or type in MATLAB, followed by pressing enter or return key at the system prompt. The screen will produce the MATLAB prompt `>>` (or `EDU >>`), which indicates that MATLAB is waiting for a command to be entered. In order to quit MATLAB, type `quit` or `exit` after the prompt, followed by pressing enter or return key.

1. Display Windows

MATLAB has three display windows. They are

- A. A Command Window which is used to enter commands and data to display plots and graphs.
- B. A Graphics Window which is used to display plots and graphs.
- C. An Edit Window which is used to create and modify M-files. M-files are files that contain a program or script of MATLAB commands.

2. Entering Commands

Every command has to be followed by a carriage return `<cr>` (enter key) in order that the command can be executed. MATLAB commands are case sensitive and lower case letters are used throughout. To execute an M-file (such as `Project_1.m`), simply enter the name of the file without its extension (as in `Project_1`).

3. MATLAB Expo

In order to see some of the MATLAB capabilities, enter the `demo` command. This will initiate the *MATLAB EXPO*. *MATLAB EXPO* is a graphical demonstration environment that shows some of the different types of operations which can be conducted with MATLAB.

4. Abort

In order to *abort* a command in MATLAB, hold down the control key and press `c` to generate a local abort with MATLAB.

5. The Semicolon (;)

If a semicolon (`;`) is typed at the end of a command, the output of the command is not displayed.

6. Typing %

When per cent symbol (%) is typed in the beginning of a line, the line is designated as a comment. When the *enter* key is pressed, the line is not executed.

7. The `clc` Command

Typing `clc` command and pressing *enter* cleans the command window. Once the `clc` command is executed, a clear window is displayed.

8. Help

MATLAB has a host of built-in functions. For a complete list, refer to MATLAB user's guide or refer to the *on-line Help*. To obtain help on a particular topic in the list, *e.g.*, inverse, type `helps inv`.

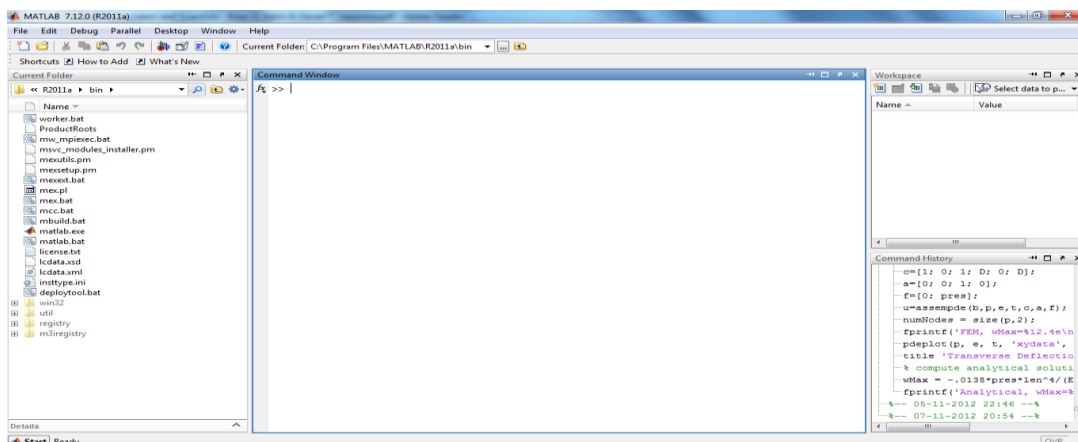


Fig: MATLAB Desktop

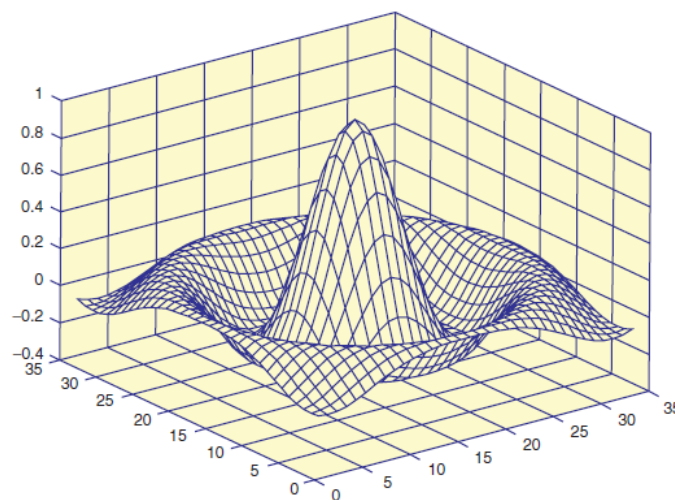
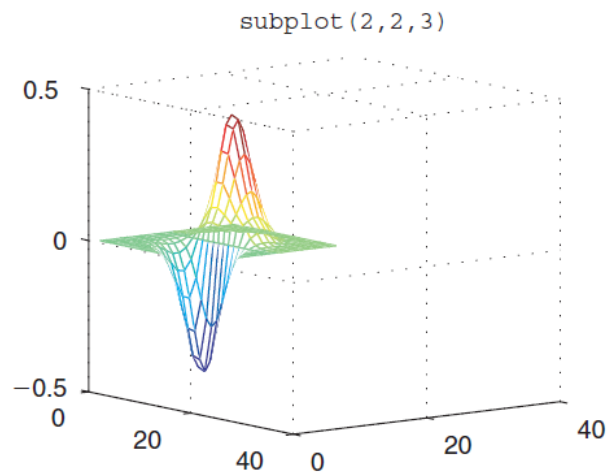
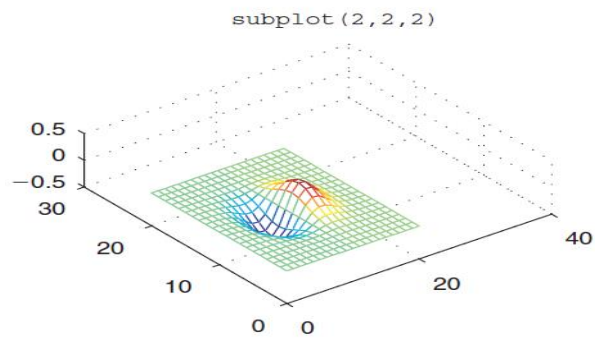
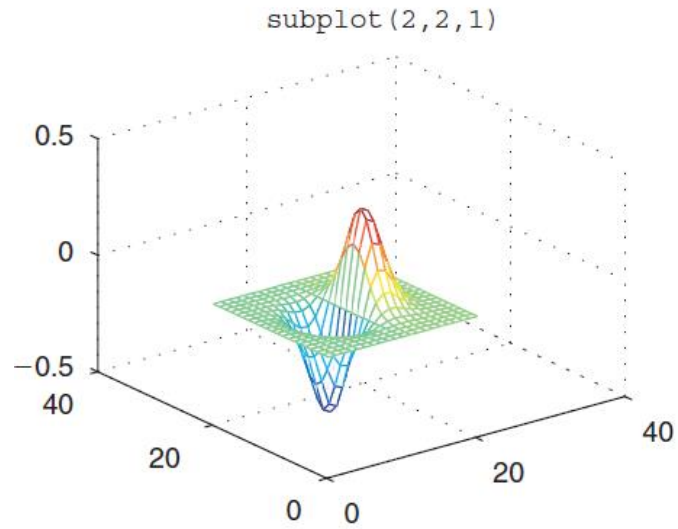


Fig.: the Mexican hat



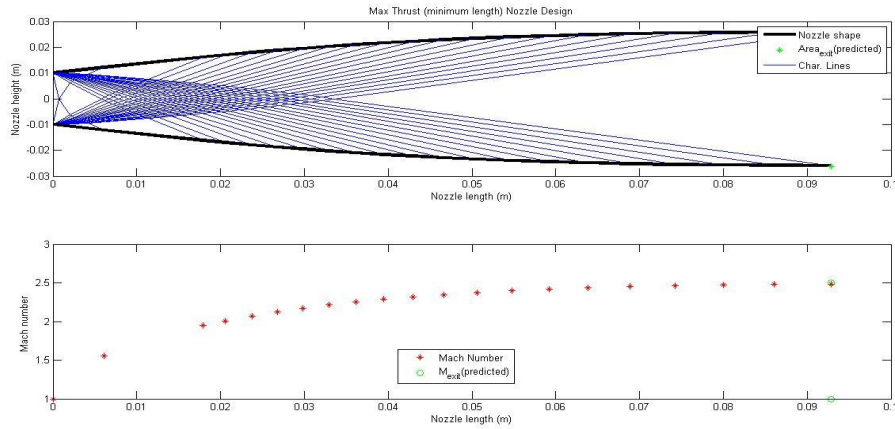


Fig: By using MAT lab coding generated MLN

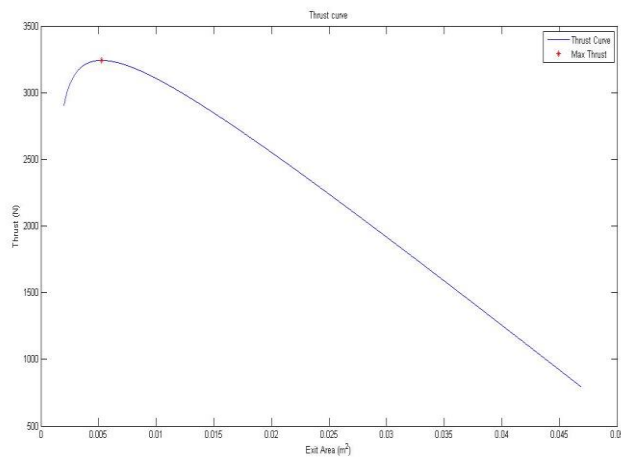


Fig :Thrust curve generation

6. MODELING AND ANALYSIS OF MINIMUM LENGTH NOZZLE

INTRODUCTION

The current session involves the analysis part of the design. The design is modeled and analyzed in ANSYS V12.0.

The design and analysis in ANSYS involves four phase of problem. They are modeling in ANSYS Design Module, Meshing in ANSYS Mesher, Set-up and Solution in ANSYS Fluent and Results in Result Viewer. These four sections are discussed in detail in present sessions.

ANSYS DESIGN MODULE

The Design Modeler application is a parametric feature-based modeler. Its modeling paradigm is to sketch 2D profiles and use them to generate features. In CAD systems, features are collections of geometric shapes with which you add or cut material from a model. In the Design Modeler application, you can also use features to slice a model into separate bodies for improved mesh generation or to imprint faces for patch loading. More generally, in the Design Modeler application you can apply features to the task of enhancing your models for the purpose of engineering simulation. The Design Modeler application's interface is similar to that of most other feature-based modelers. The program displays menu bars along the top of the screen.

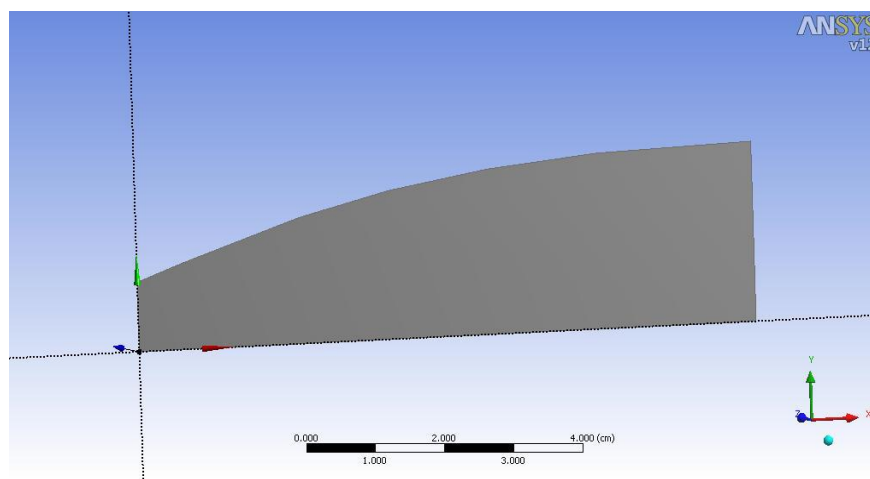


Fig : Minimum length nozzle model

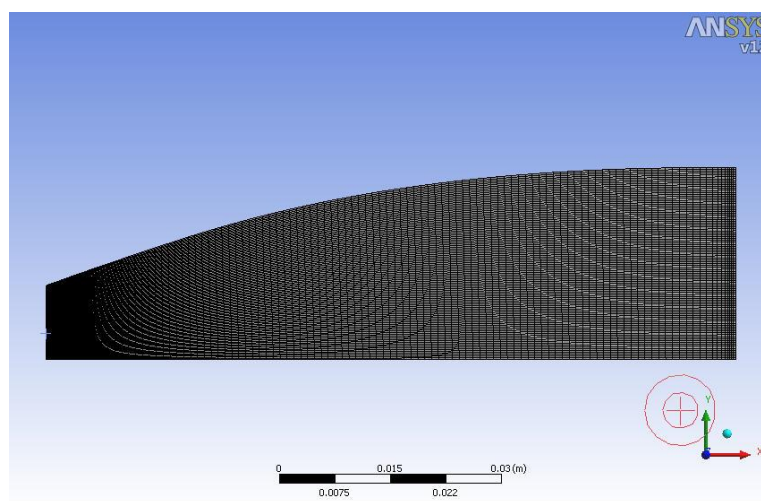


Fig: Meshed model

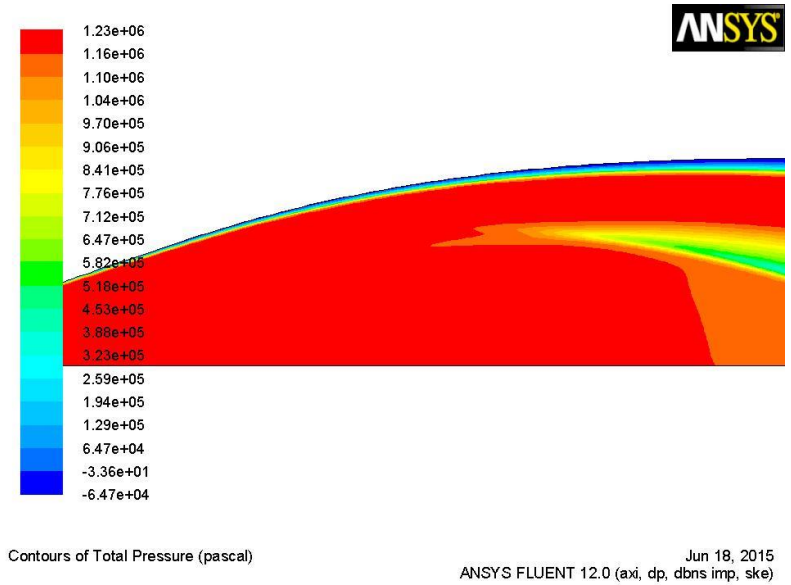


Fig: Contours of Total pressure

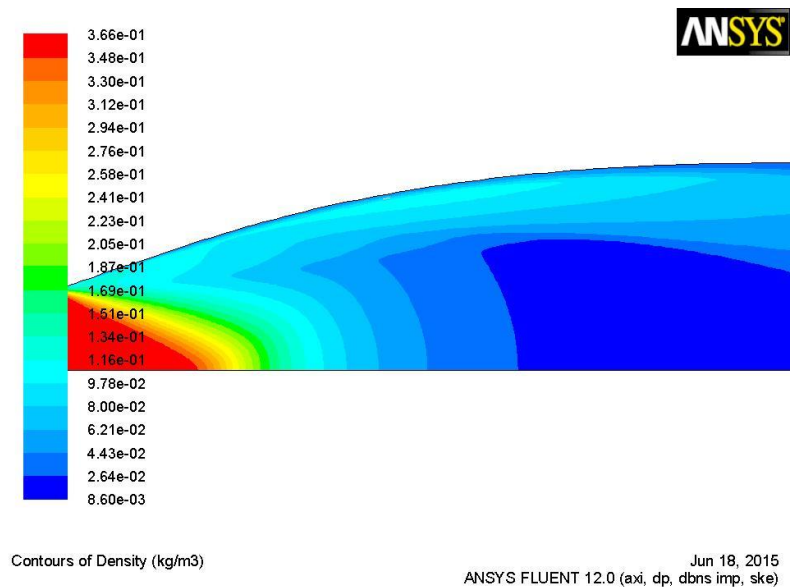


Fig : Contours of density

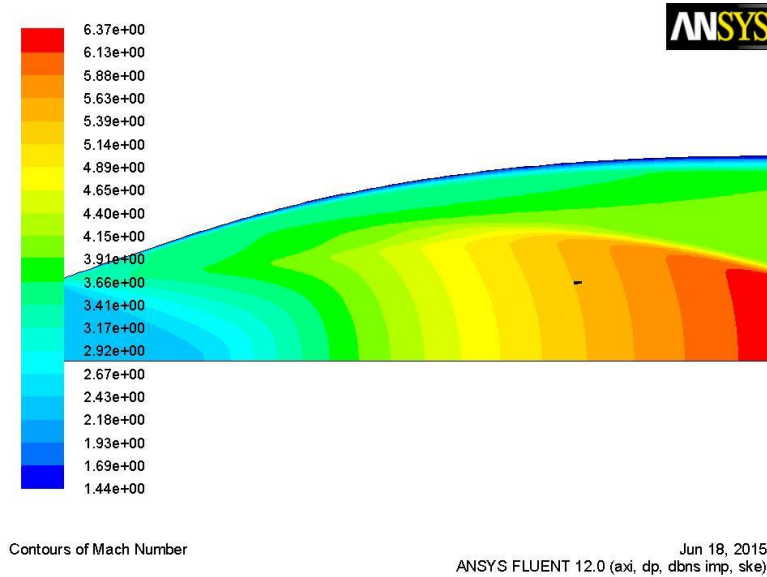


Fig: contours of Mach number for MLN, Area Ratio = 0.00281 with $T_o = 2000$ K, $P_o = 1.2$ MPa

MLN Plots

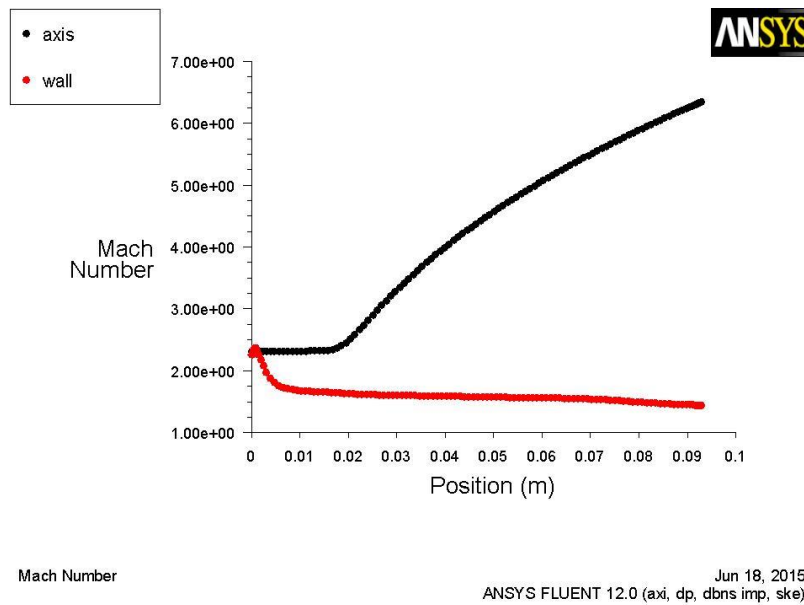


Fig: Minimum length nozzle Mach number plot

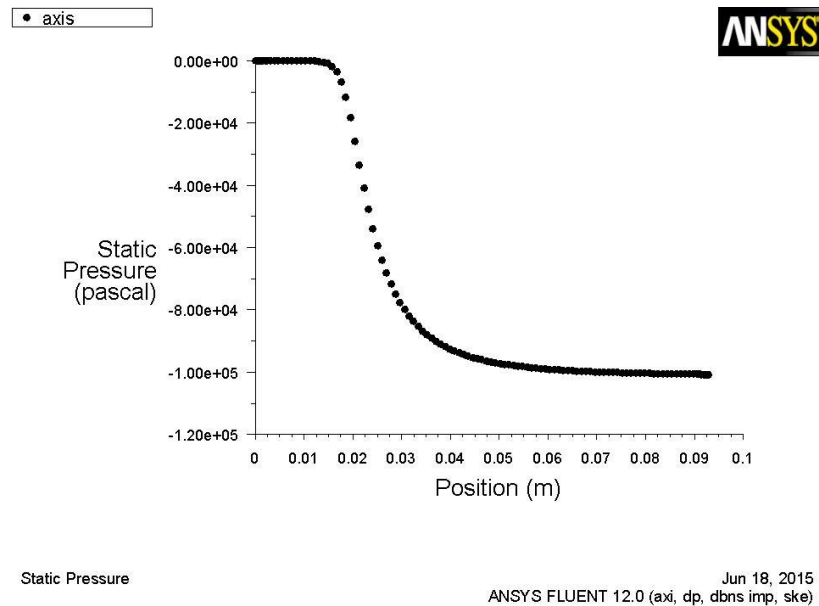


Fig : Minimum length nozzle pressure plot

7. RESULTS AND DISCUSSION

The design of minimum length supersonic nozzle is capable of producing minimum length nozzle by contracting the expansion section. With the contraction of the expansion section, the total length of the nozzle reduces. In the above design, the length of the supersonic nozzle is minimum, since the expansion section is minimum. In fact, the expansion section is contracted to a point at the end of the throat. The straightening section was right at the core of designing concentration. The straightening section is responsible for the uniform flow at outlet. Thereby, proper designing of the straightening section is imperative. In fact, straightening section is employed to control the way of interaction of the fluid coming out of the engine or the blower with the atmospheric fluid outside the nozzle. The efficiency and deficiency of the nozzle both depends on the design of the straightening section. All losses that occur in the actual flow conditions are by somewhat means relevant to the design of the straightening section. Any attempts to reduce these losses deals with analysis of the flow pattern in the straightening section. Earlier, it was mentioned that the nozzle is being designed for the optimum exit Mach number. It should be recalled that the streamlines are turned away from the axis and, afterwards, they are turned back toward the axis in the diverging section. The turning away of the streamlines occurs at the expansion section, whereas the turning in of the streamlines occurs at the cancellation or the straightening section. The turning away angle is a function of local Mach number. Thereby, it is crystal clear to state that the last local as well as maximum turning away angle plays the vital role to define the exit Mach number. The minimum length is achieved in the above output with the mesh

generated by 10 characteristic lines. The reflection section begins from the length of 0.000847m and stretched to the length of 0.03352m. It should also be mentioned that the throat of the nozzle is 0.025m according to the design assumptions. The expansion waves are completely cancelled at the length of 0.0856m and height of 0.0256m. When the minimum length is achieved in the above output with the mesh generated by 30 characteristic lines then the reflection section begins from the length of 0.000847m and stretched to the length of 0.03326m. The expansion waves are completely cancelled at the length of 0.0873m and height of 0.0265m. In this output both the length and height have increased, but the reflection section has reduced. When the minimum length is achieved in the above output with the mesh generated by 50 characteristic lines then the reflection section begins from the length of 0.000847m and stretched to the length of 0.0331m. The expansion waves are completely cancelled at the length of 0.0875m and height of 0.0267m. In the above output both the length and height have increased slightly, but the reflection section has reduced. Again when the minimum length is achieved in the above output with the mesh generated by 100 characteristic lines then the reflection section begins from the length of 0.000847m and stretched to the length of 0.03303m. The expansion waves are completely cancelled at the length of 0.0877m and height of 0.0269m. In the above output both the length and height have increased slightly, but the reflection section has further reduced. When the minimum length is achieved in the above output with the mesh generated by 200 characteristic lines then the reflection section begins from the length of 0.000847m and stretched to the length of 0.03301m. The expansion waves are completely cancelled at the length of 0.0878m and height of 0.0269m. In the above output both the length and height have increased slightly, but the reflection section has reduced. It is observed that with the refinement of mesh the result becoming steadier.

8. CONCLUSION

The complete design philosophy is developed and implemented for the ideal conditions. To address the actual conditions, the consideration should be made on account of the phenomena due to the viscous effect, pressure difference with respect to the back pressure, heat conduction and so on. The design presented here can be utilized to compare with the other nozzle designs regarding to the specific design conditions. The simulation program of the practical supersonic nozzle can be developed depending on this design with the considerations of the losses take place in real time.

BIBLIOGRAPHY

- [1] Al-Ajlouni M., An Automatic Method for Creating the Profile of Supersonic Convergent-Divergent Nozzle, Journal of Mechanical and Industrial Engineering, vol 4 No. 3, 2010, pp. 404-411
- [2] Alkhimov A.P., Kosarev V.F. and Klinkov S.V., The Features of Cold Spray Nozzle Design, Institute of Theoretical and Applied Mechanics SB RAS, Journal of Thermal Spray Technology Volume 10(2), ASM International, Novosibirsk, 2001, pp 375
- [3] Amardip Ghosh, Supersonic Nozzle Design Using 2D method of characteristics, Department of Aerospace Engineering, University of Maryland.

- [4] Carmichael Ralph, How do you compute the inverse of the Prandtl-Meyer Function?, Public Domain Aeronautical Software, Santa Cruz, 2007.
- [5] Champagne V. K. et al., Comparison of Empirical and Theoretical Computations of Velocity for a Cold Spray Nozzle
- [6] Champagne V. K. et al., Theoretical and Experimental Particle Velocity in Cold Spray, Journal of Thermal Spray Technology, vol 20 No. 3, 2011, pp. 425{431
- [7] Dykhuizen R.C., Smith M.F., Gas Dynamic Principles of Cold Spray, ASM International, JTTEE5 7, 1998, pp. 205{212.
- [8] Francois R., Contribution to the development of a Cold Gas Dynamic Spray System (C.G.D.S.) for the realization of nickel coatings, Sciences des procedes de Ceramiques et Traitements de Surface, Universite de Limoges, These No. 45, 2005
- [9] Jodoin B., Cold Spray Nozzle Mach Number Limitation, Journal of Thermal Spray Technology, vol 11, No. 4, 2002, pp. 496{507 83
- [10] Gartner F, Schmidt T., Stoltenho_ T. and Kreye H.,Recent Developments and Potential Applications of Cold Spraying, Advanced Engineering Materials 8, No. 7, 2006
- [11] Gartner F., Stoltenho_ T., Schmidt T. and Kreye H.,The Cold Spray Process and Its Potential for Industrial Applications, Journal of Thermal Spray Technology, Vol 15, No. 2, 2006, pp. 223{232
- [12] , Ghajar Afshin J., Engineering Handbook CRC Chap 36, Compressible flow, Oklahoma State University, CRC Press LLC, 2005.
- [13] Grujicic M., Tong C., DeRosset W. S. and Helfritch D., Flow Analysis and Nozzle-Shape Optimization for the Cold-Gas Dynamic-Spray Process, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, Vol 217, 2003, pp. 1603{1613
- [14] Grujicic M., Zhao C. L., Tong C., DeRosset W. S. and Helfritch D.,Analysis of the impact velocity of powder particles in the cold-gas dynamic-spray process; Materials Science and Engineering A368, Elsevier B.V., 2004,pp. 222{230
- [15] Helfritch D. and Champagne V., A Model Study of Powder Particle Size E_ects in Cold Spray Deposition, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, 2008.
- [16] Karimi M. et al., Numerical Simulation of the Cold Gas Dynamic Spray Process, Journal of Thermal Spray Technology, ASM International, Vol 15 (4), 2006
- [17] Khine T. Naung, Nyunt Soe, Numerical Approach for Determination of Supersonic Nozzle Flow Pattern, GMSARN International Conference on Sustainable Development: Issues and Prospects for the GMS, 2008, pp. 12{14
- [18] Kim Hyung-Jun, Leeb Chang-Hee , Hwanga Soon-Young, Superhard nano WC12% Co coating by cold spray deposition, Materials Science and Engineering A 391, 2005, pp. 243 248
- [19] Klassen T. and Kreye H., The Cold Spray Process and its Optimisation, Institute of Materials Technology, Helmut-Schmidt-University, 2006.
- [20] Klassen Thomas, 84 http://www.hsu-hh.de/werkstoffkunde/index_P4OTiQPRdTHq9uNv.html