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Characterisation of Mach number 1.5 and 2 Nozzle Jets using Computational Techniques

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***Abstract:** In this paper a supersonic nozzle was designed using the MOC method and the nozzle contour has been created. The computational model was developed to model the characteristics of the jet of Mach number 1.5 & Mach number 2 nozzles. The computational model was created with compressible flow field properties in order to get the most accurate result. The pressure inlet and outlet boundary conditions have been applied with viscous flow solver. In order to get the shock flow visualization and high-speed jet characteristics the exit has been extended to 5D vertical and 15D horizontal and the virtual atmosphere has been created. For both models, the CAA (computation acoustical analysis) carried out using flows, Williams and Hawkings acoustic solver to get far-field noise radiation. The experimental technique and future works were discussed. The Jet characteristics of two nozzles were examined and noise sources have been compared.*

***Keywords:** Supersonic nozzle, shock visualization, CAA, acoustic analysis, high-speed jet, computational technic for noise radiation.*

I. INTRODUCTION

With the development of science and technology, lunar missions are possible nowadays. To travel such a vast and long-distance, high-speed vehicle are needed and necessary. In such cases, high-speed aerodynamics plays a vital role in designing both aerodynamic and propulsive components of the vehicle. In such cases, the control of the flow field is essential because the uncontrolled flow field may cause serious and undesirable effects of the mission. The nozzle is one of the important components in the rocket, missiles, and aircraft. Especially high-speed nozzle design and flow control are somewhat difficult compared to others because it is a thrust generating part. A nozzle is a passage used to transform pressure energy into kinetic energy. A convergent-divergent nozzle used to generate supersonic jet flow.

A jet may be defined as a pressure drove shear flow exhibits a characteristic that the width-to-axial distance is a constant. It may also define as continuous fluid flow issuing from the orifice into a medium of lower speed. It is further classified into the free jet, co-flowing jet, impinging jet and wall jet according to its nature of the flow.

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Jet and its characteristics are important factors in the nozzle design which is very important in the design of rockets and missiles. The supersonic nozzle design is the key to designing rockets, missiles, and jet engines because the nozzle determines the major performance criteria of rockets, missiles, and jets. But supersonic nozzle design is the complicated process because the flow is compressible and involving shocks. For designing a minimum length nozzle, the Method of characteristics is the well-known method in the field of supersonic nozzle design. The main objective of my research is to design a supersonic nozzle for Mach numbers 2 & 1.5 and compare its jet characteristics. A computational model is created to study the characteristics of the nozzle. In this work the nozzle is designed with exit Mach number 1.5 & 2, then analyzed with broad NPR (2,3,4,7) values. To predict far-field acoustical characteristics Flows Williams and Hawkings acoustic prediction method are applied.

II. NOZZLE DESIGN AND ANALYSIS

Designing technics of the supersonic nozzle is broadly discussed [2], and the software for automatic contour generation has been created in [3]. The detailed description of the Method of Characteristics is clearly discussed in [1] and the simple program has been developed by [1]. Using this MOC program the nozzle contour was plotted successfully and the details are discussed. The work is done with a moderate expansion ratio (Area ratio 1.5) and 1.5<NPR<2.4. In [4] the k-w turbulence model is used to study the turbulence characteristics.

III. THE MOC PROGRAM

The program is written in FORTRAN language. Using this program, nozzle contour was generated. The input parameters for this program are an inlet and exit Mach number, No of characteristics, inlet area, and specific heat ratio. The output of the program contains the coordinates of the specific nozzle. The nozzle contour for Mach 2 & Mach 1.5 is given in below figures 1 & 2.

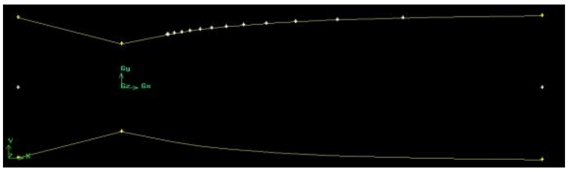

Fig. 1. Nozzle contour of Mach number 2

Fig.2. Nozzle contour of Mach number 1.5

IV. THE MOC PROGRAM

The program is written in FORTRAN language. Using this program, nozzle contour was generated. The input parameters for this program are an inlet and exit Mach number, No of characteristics, inlet area, and specific heat ratio. The output of the program contains the coordinates of the specific nozzle. The nozzle contour for Mach 2 & Mach 1.5 is given in below figures 1 & 2.

V. ONE DIMENSIONAL ANALYSIS OF NOZZLE

The program is written in FORTRAN language. Using this program, nozzle contour was generated. The input parameters for this program are an inlet and exit Mach number, No of characteristics, inlet area, and specific heat ratio. The output of the program contains the coordinates of the specific nozzle. The nozzle contour for Mach 2 & Mach 1.5 is given in below figures 1 & 2.

A. WITH MACH NUMBER 2

Exit Mach number = 2
Area ratio (A_e/A^*) = 1.688 (from isentropic table)
Area ratio (A_e/A^*) = 0.81893/0.5
= 1.6378
Error = 1.688-1.6378/1.688 X 100
= 3 %

Now the nozzle geometry is given below,
Area of throat = o.5 cm^2
Area of the exit = 0.81893 cm^2
Area of the inlet = 1.136 cm^2
Length of the nozzle = 5.20898 cm
(the nozzle has one-unit length in the z-direction and symmetrical about the x-axis)

Now let us move to the preliminary calculations to set up settling chamber pressure. This is for correctly expanded flow.
P_e = 101325 pa
T_e = 288.5 k
From isentropic relation
$T_0/T_e = 1+\frac{\gamma-1}{2}Me2$
= 1.8
T_o = 518.67
$P_0/P_e = (1+\frac{\gamma-1}{2}Me2)\frac{\gamma}{\gamma-1}$
P_o = 7.824 P_e
P_0 = 792770 pa

B. WITH MACH NUMBER 1.5

Exit Mach number = 1.5
Area ratio (A_e/A^*) = 1.176 (from isentropic table)
Area ratio (A_e/A^*) = 0.5769/0.5
= 1.1539
Error = 1.176-1.1539/1.176 X 100
= 1.3 %
Now the nozzle geometry is given below,
Area of throat = o.5 cm^2
Area of the exit = 0.5769 cm^2
Area of the inlet = 0.588 cm^2
Length of the nozzle = 1.97 cm
(the nozzle has one-unit length in the z-direction and symmetrical about the x-axis)
Now let us move to the preliminary calculations to set up settling chamber pressure.
P_e = 101325 pa
T_e = 288.5 k
From isentropic relation
$T_0/T_e = 1+\frac{\gamma-1}{2}Me2$
= 1.45
T_o = 417.6
$P_0/P_e = (1+\frac{\gamma-1}{2}Me2)\frac{\gamma}{\gamma-1}$
P_o = 3.67 P_e
P_0 = 371967 pa

VI. COMPUTATIONAL DOMAIN FOR NOZZLE ANALYSIS

For performing advanced analysis, the virtual atmosphere is extended with nozzle lip for the dimensions of 5D in the y-axis and 15D in the x-axis as shown in figure 3. By extending the nozzle lip for 15D,5D we can able to visualize the self-similar flow, shock cells, and turbulence intensity. We can also able to determine the jet characteristics. The geometry and physical domain are illustrated in figure 3.

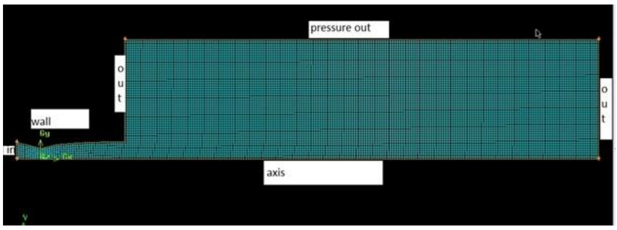

Fig .3. Flow domain of the Mach 2 nozzle.

VII. NOZZLE ANALYSIS

The analysis is done for the following nozzle with corresponding NPR values.

Table-I: Solver settings

s. no	Mach number	NPR	Solver settings
1	2	4	Axisymmetric, unsteady, density-based, K-w model
2	2	7.82	Axisymmetric, unsteady, density-based, K-w model, Foochow's Williams, and Hawkins acoustic model
3	1.5	3	Axisymmetric, unsteady, density-based, Spalart-Alambars model

VIII. RESULTS AND DISCUSSIONS

The below results are shown the contours of static pressure, velocity, Mach number and turbulence characteristics of the corresponding Mach number and NPR. The results of the CAA shown the sound pressure level of the Mach 2 nozzle for NPR 7.82.

The plasma actuator computational model has shown the results of induced noise reduction of 2 dB which is the same as the results of [6].

A. RESULTS FOR Mach 2 NPR 4

From the below results we can know that the nozzle is over expanded. Hence it the jet experiences additional compression at the exit. The nozzle jet experience high turbulence compares to others. The shock cells are visible. Inside the shock cell, at the centre Mach number is higher; around the shock cell, Mach number is lower. It is clear that, the mixing regions of the shock with rest air, experience higher turbulence.

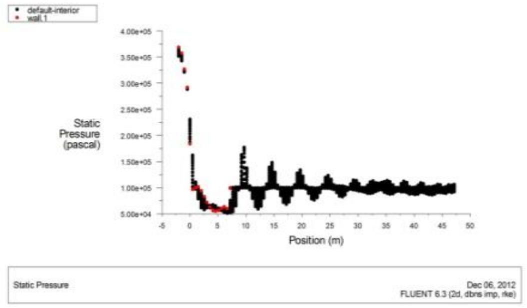

Fig. 4. Centerline static pressure xy plot

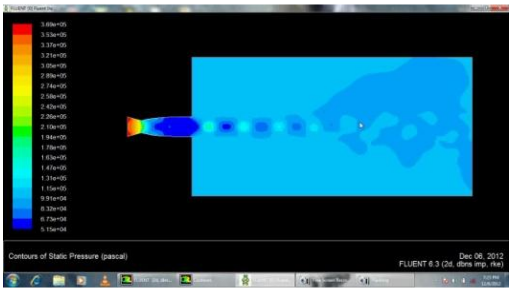

Fig. 5. Static Pressure Contour

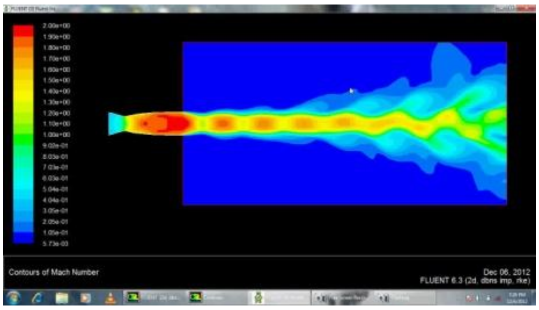

Fig .6. Mach Number Contour

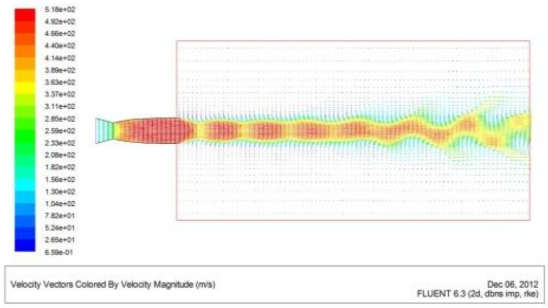

Fig .7. Velocity Vector Contour

B. RESULTS FOR Mach 2 NPR 7.82

From the below results, we can know that the nozzle is correctly expanded. The strong normal shock appears at the exit and the followed shock cells are appearing. The nozzle jet experience low turbulence compares others. The shock cells are visible. Inside the shock cell, at the centre Mach number is higher; around the shock cell Mach number is lower. It is clear that, the mixing regions of the shock with rest air, experience higher turbulence. CAA results are shown below. Using this we can estimate acoustical characteristics of the nozzle.

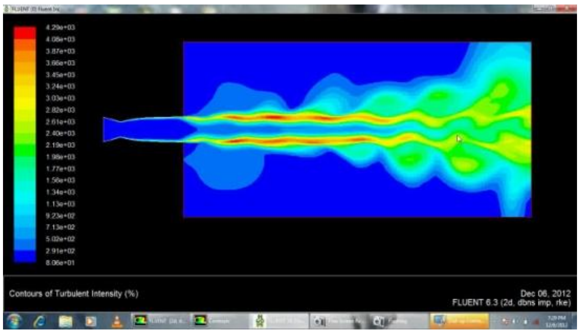

Fig .8.Turbulent intensity contour

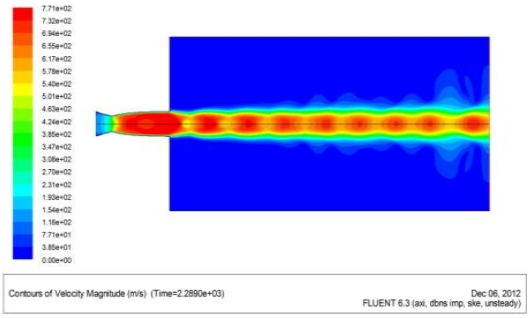

Fig. 9. Velocity Vector Contour

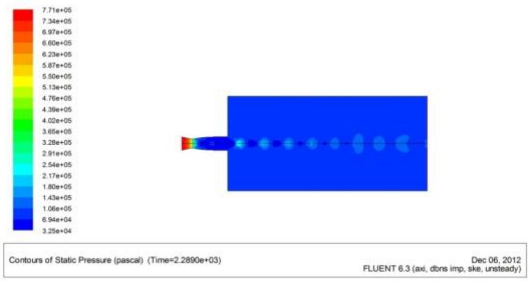

Fig.10. Pressure Contour

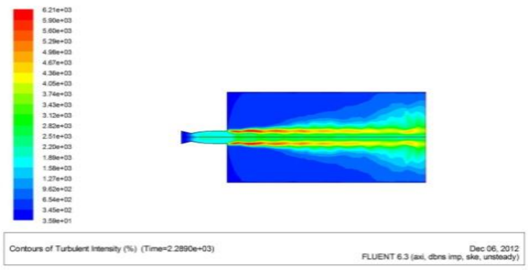

Fig. 11. Turbulence Contour

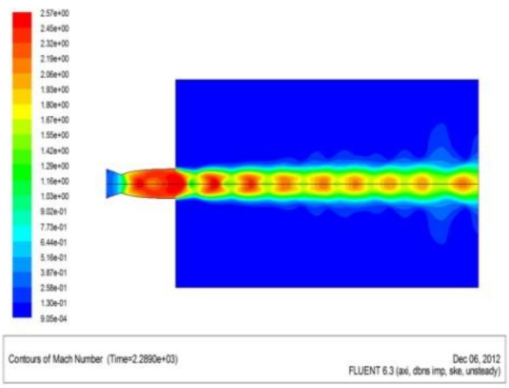

Fig 12. Mach number Contour

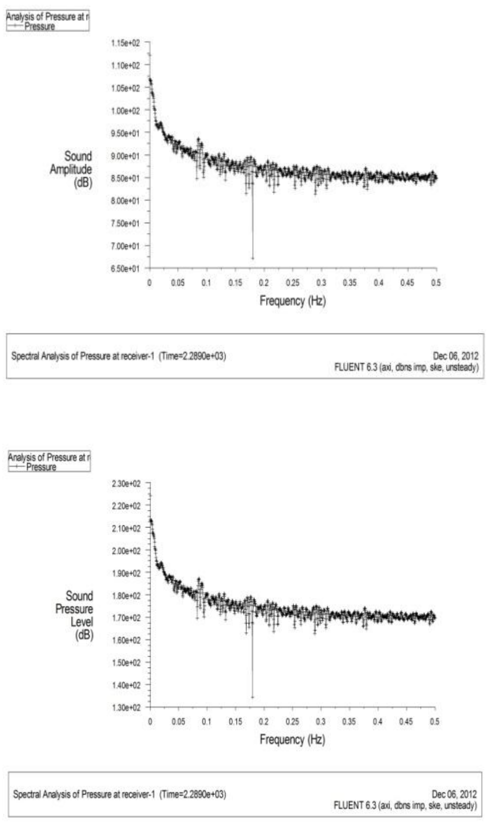

Fig 13 CAA results

C. RESULTS FOR Mach 1.5 NPR 3

From the below results we can know that the nozzle is over expanded. Hence, nozzle jet experience additional compression at the exit. This is near to the transonic region, so one strong shock cell is appearing at the exit followed by a single jet plum. Jet experiences strong turbulence compare to Mach 2 nozzle jet.

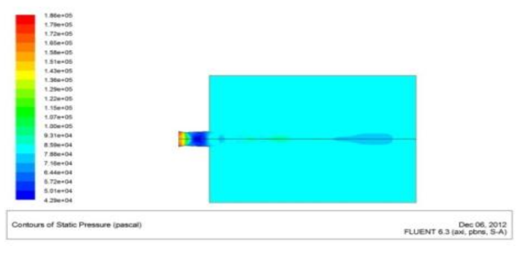

Fig 14 Pressure Contour

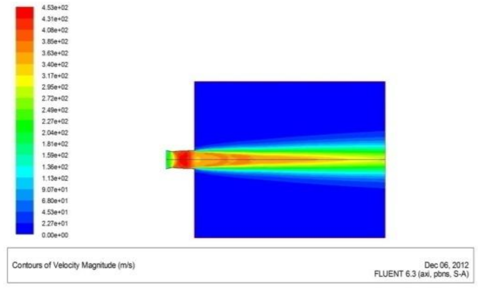

Fig. 15. Velocity Contour

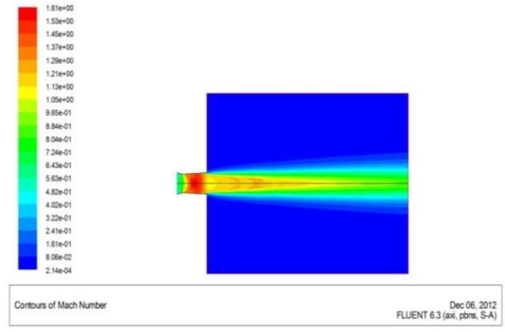

Fig. 16. Mach number contour

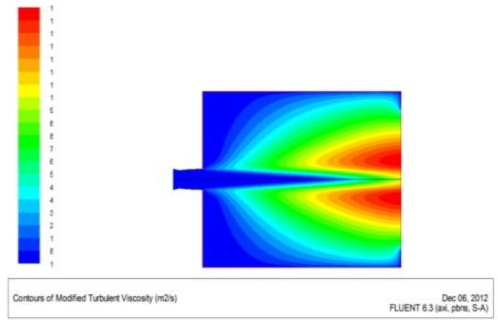

Fig. 17. Turbulence Contour

D. SUMMARY

	Mach number 1.5	Mach number 2
Jet length	3D	10D and continue
Turbulent	After 10D strong	6D
Acoustical	Depends mainly on shock	Turbulent and shock cell

E. FUTURE WORKS

The next step in this work is to develop a numerical model for both the nozzle to verify the under, over and correctly expanded state conditions. Then the new active flow control technique will be applied to control over the supersonic flow. The next step is to create the computation model for high-speed jet control using a plasma actuator. But our present computational tools support combined pressure inlet and velocity inlet in incompressible flow regions only. Unfortunately, there is no numerical model is available for combined pressure and velocity inlet boundary condition for compressible flow problems. So, we need to develop our computational and numerical tools for performing combined velocity and pressure inlet flow in the compressible flow region.

Or else we need to change the computation method from velocity inlet into other boundary conditions which will satisfy the experimental result. In parallel to this work to study the experimental high-speed flow control, the simplified experimental model has been created as below.

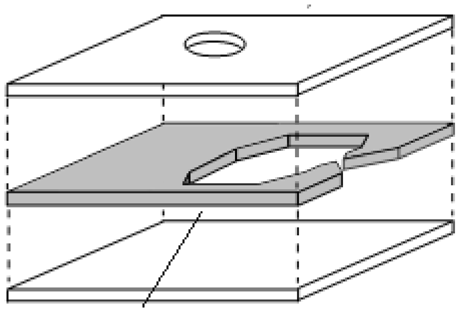

Fig. 18. Concept for nozzle manufacturing

IX. CONCLUSION

The nozzle characteristics are determined. It is clear that Mach number 1.5 jets are having 3D length while Mach number 2 jet having 8D length. The noise is developed in Mach number 1.5 is highly contributed by turbulent while for mach 2 is highly contributed by shock cell. So, the future works will be concentrated to reduce turbulent and shock-induced noise. The Future works have been listed out and needed developments are listed.

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