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**NUMERICAL AND EXPERIMENTAL INVESTIGATIONS OF
THE NOZZLE GEOMETRY IN SUPERSONIC MIXING.**

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ABSTRACT

Effective mixing of two supersonic streams in a short mixing chamber is a major challenge. Active and passive methods are used to enhance the mixing. Nozzle geometry, different nozzle configurations a concept of passive method, considered in this paper to enhance the mixing. In this paper, both numerical and experimental investigation of oval nozzles presented. Mixing performance was studied for selected oval nozzles and the oval geometry is varied by changing the aspect ratios of 1:2, 1:3 and 1:4. A mixing tube with an aspect ratio (L/D) of 4 was used to assess the mixing performance. The performance parameters such as momentum flux, degree of mixing and stagnation pressure loss are used to analyze the study. Among three different geometries, the oval nozzle with an aspect ratio of 1:3 showed the highest performance.

Keywords: Oval nozzle, Supersonic mixing, Momentum flux, Degree of mixing.

NOMENCLATURE

L	Length of the mixing tube (mm)
D	Diameter of the mixing tube (mm)
DOM	Degree of mixing
PDF	Pressure drop factor
R	Radius of the mixing tube (mm)
	Radial distance from the axis (mm)
M	Mach number
p	Static pressure (MPa)
γ	Ratio of specific heats

μ	Momentum flux (MPa)
A.R	Aspect ratio
Φ	Uniformity factor
Φ_{UM}	Uniformity factor of unmixed jet

1. INTRODUCTION

In order to obtain more efficient and reliable hypersonic propulsion system, mixing of two high speed streams in a short mixing duct of short residence time is a basic requirement. Samitha et al. [1] experimentally and numerically studied the mixing performance of three lobed clover nozzle with rectangular cavity of different aspect ratios and compare with that of conventional conical nozzle with cavity in coaxial supersonic streams of Mach number 2 and 1. Samitha et al. [2] were conducted experimental study on supersonic mixing using three lobed nozzle. The result showed a complete mixing of the streams with marginal loss in stagnation pressure loss within a short mixing length. Three lobbed clover nozzle is introduced to add passive mixing. Studies towards this direction [3] showed that a clover nozzle, which is a class of radially lobbed nozzle, provides better pressure recovery compared to normal lobbed nozzle. Deepu et al. [4] numerically studied that shock induced vortex generation enhance mixing and reaction. It is found that the shock reflections are responsible for blocking the development of jets and thereby creating the low velocity region cavity.

S. Jeyakumar and P. Balachandran [5] studied that wall mounted cavities enhance momentum mixing of two supersonic streams within a mixing tube at the cost of marginal loss in stagnation pressure. E.Rajakuperan et al. [6] experimentally studied underexpanded jets from oval sonic nozzles. The results revealed that the jet spreading rate in the minor axis plane of the nozzle was much higher compared to that in the major axis plane. Srikrishnan et al. [7] were experimentally studied the momentum fields when a petal nozzle is used. Papamoschou and Roshko [8] conducted experimental and theoretical studies showed that the growth rate of shear layer that controls the mixing of co-axial supersonic stream extremely slow.

In this study the passive mixing technique is used by changing the initial condition of the flow in the mixing tube. The objective of the present work is to study the effect of oval shaped nozzles by varying the aspect ratios (1:2,1:3,1:4) and analyzed numerically and experimentally using the mixing tube of $L/D=4$. In order to compare the performance of oval nozzle and conical nozzle, both the nozzles were chosen so that the designed exit Mach number and throat area are the same and the area ratio used for both nozzles is 2.005.

2. COMPUTATIONAL METHODOLOGY

Numerical analysis has been done using commercial CFD software FLUENT 6.3.26. The grid generation and modelling is done using the pre-processor GAMBIT 2.4.6. The computational domain for numerical analysis is shown in fig .1.

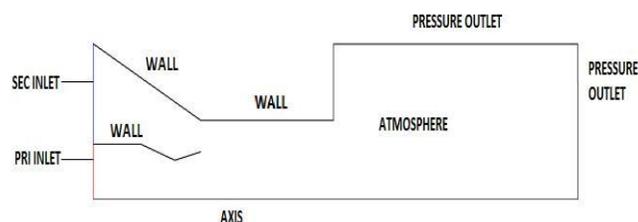


FIGURE 1. COMPUTATIONAL DOMAIN NUMERICAL ANALYSIS

In the case of circular nozzle, a two dimensional axisymmetric model was created and three dimensional geometry for Oval nozzles. It was found that the oval shaped nozzle exhibits symmetry about the major and minor plane such that the included angle between them is 90 degree. Computational grid for Oval nozzle are shown in figure.2 The domain exit length is taken as 10 times the diameter of the mixing tube to ensure the interaction at the exit with atmospheric condition.

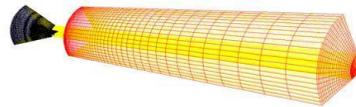


FIGURE 2. GRID SYSTEM FOR OVAL NOZZLE

The inlet conditions of primary nozzle is 1MPa, 300K at primary inlet. For secondary nozzle, it is 0.2MPa and 300K . The outlet condition is set with atmospheric properties (0.1MPa and 300K) set at outlet. Analysis is done with k- ω turbulence model with coupled implicit solver and Y^+ value between the range 300-500.

3. GRID INDEPENDENCE STUDY

A grid independence study has been conducted at an optimum grid for two dimensional and three dimensional numerical simulations. DOM is the parameter checked during grid independence study. The table 1. shows the grid independence study according to Richardson criteria. The results are found to be insensitive beyond 62343 cell for two dimensional conical nozzle and 202500 for the three dimensional oval nozzles

TABLE 1. GRID INDEPENDENCE STUDY

Nozzle type	Number of cells	DOM
Oval nozzles	90000	0.8446
	135000	0.8550
	202500	0.8550
	272000	0.8448
Conical nozzles	41562	0.59
	62343	0.60
	93514	0.58

4.GOVERNING EQUATIONS

$$\begin{aligned} & \text{Continuity equation} \\ & \nabla \cdot (\rho U) = 0 \end{aligned} \quad (1)$$

$$\begin{aligned} & \text{Momentum equation} \\ & \nabla \cdot (\rho U U) + \nabla p = \nabla \cdot \tau \end{aligned} \quad (2)$$

$$\begin{aligned} & \text{Energy equation} \\ & \nabla \cdot (\rho U e) = -\nabla \cdot q + \nabla \cdot (U \tau) - \nabla (p U) \end{aligned} \quad (3)$$

e is the total energy

5. DEFINITION OF MIXING PARAMETERS

5.1 MOMENTUM FLUX DISTRIBUTION (μ)

The momentum flux can be associated with either mean velocity components, internal gravity waves or with the turbulent velocity fluctuation. Flux distribution at the exit of the supersonic combustors in the radial direction is the measure of bulk mixing.

$$\mu = p(1 + \gamma M^2) \quad (4)$$

Where p is the static pressure and M is the Mach number calculated from measured values of stagnation pressure. The behavior of the momentum flux of all Oval nozzles showed nearly flat as in fig. 4,5,6 . The one with aspect ratio 1:3 & 1:4 showed the complete mixing.

5.2 DEGREE OF MIXING (DOM)

To make a comparison between the mixing performance of Oval nozzles and circular nozzles based on a quantitative assessment of the level of mixing achieved, a dimensionless parameter called uniformity factor Φ is used and it is defined as

$$\Phi = 1 - \left[\frac{\sigma_{\mu}(x)}{\mu_{av}(x)} \right] \quad (5)$$

where $\sigma_{\mu}(x)$ is the standard deviation of the radial distribution of momentum flux at a given axial location in the mixing tube, $\mu_{av}(x)$ is the average of momentum flux along radial line at the location considered. This factor is a measure of the uniformity of the momentum flux distribution in radial direction, at a given location. For perfectly mixed flow, the distribution has to be uniform. A uniformity factor is used to define a mixing parameter, called, Degree of Mixing (DOM).

$$DOM = \frac{(\Phi - \Phi_{UM})}{(1 - \Phi_{UM})} \quad (6)$$

5.3 PRESSURE DROP FACTOR (PDF)

Stagnation pressure loss indicates the measure of the efficiency of a process. The loss in stagnation pressure is characterized by defining a parameter called Pressure Drop Factor (PDF). In the case of nozzle area weighted averaged stagnation pressure is calculated along major and minor plane. The PDF is defined as the difference between the area weighted average of stagnation pressure at the inlet of the primary nozzle and exit of the mixing tube, normalized by the area weighted average of the primary nozzle inlet stagnation pressure. PDF values were obtained from numerical.

$$PDF = 1 - \left(\frac{P_{OE}}{P_{OI}} \right) \quad (7)$$

P_{OI} - Area weighted average of stagnation pressure at nozzle inlet.

P_{OE} - Area weighted average of stagnation pressure at mixing tube exit.

A_p & A_s - Area of primary and secondary inlet.

6. EXPERIMENTAL SETUP

For experimental study conventional convergent-divergent Conical nozzle and three Oval shaped nozzles by varying aspect ratios were designed and fabricated.

The primary nozzle was designed to give supersonic flow at the exit with Mach no: 2 and sonic flow at secondary nozzle exit. The experimental setup as shown in fig 3. consists of Air supply system, test set up, XYZ traversing mechanism, digital manometers, pressure probe etc. Air supply system consist of a high pressure compressor of 4MPa working pressure and 3 storage tanks capable of capacity 3000l with 44bar pressure. The test set up which consists of primary and secondary settling chambers, primary nozzle, secondary nozzle and mixing tube. Primary air was supplied to the inlet conditions of 10bar and 300K and secondary at 2bar and 300K through 0.0254m diameter pipe line consisting of valves for controlling the flow.

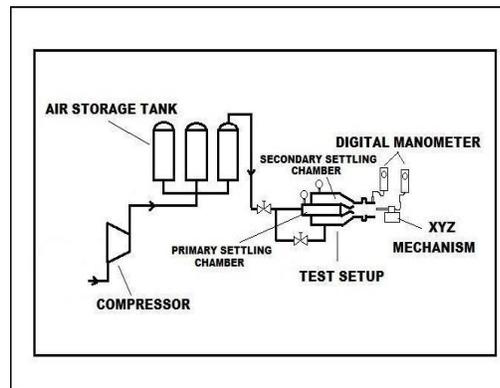


FIGURE 3 . EXPERIMENTAL SETUP

To measure the static pressure, a digital manometer is provided on the mixing tube. XYZ motion mechanism for adjusting the probe position so as to take the stagnation pressure measurements at various positions along the radial direction at the exit of the mixing tubes is also provided.

7. RESULTS AND DISCUSSIONS

7.1 MOMENTUM FLUX (m)

Figure 4, 5, 6 shows the radial distribution of momentum flux at the exit of mixing tube for various configurations. r/R denotes the radial distance normalized by radius of the mixing tube (R). The variation of momentum flux with r/R along the major and minor planes are presented. The momentum flux distribution continues to be non uniform for conical nozzle where as a considerable improvement achieved along the major plane and minor planes of the oval nozzle.

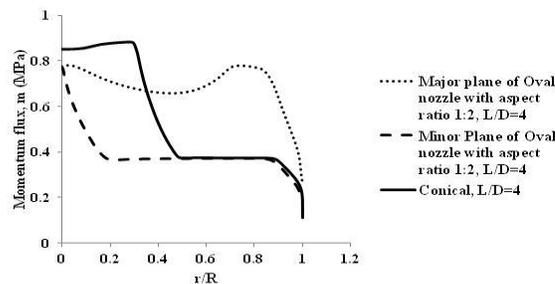


FIGURE 4. DISTRIBUTION OF MOMENTUM FLUX OVAL NOZZLE WITH A.R 1:2

Along the major plane of Oval configuration, the momentum flux shows a sharp increase near the wall due to the free expansion of the working fluid, hence velocity and Mach number increases. The momentum flux near wall ($r/R= 1$) is lower for conical when compared to Oval configuration which indicated a poor mixing with conical nozzle. The mixing between the two streams is the result of only the shear layer interaction between streams in conical configuration whereas in Oval configuration mixing enhancement may be due to the combined effect of shear layer and passive technique, which is adopted in the study.

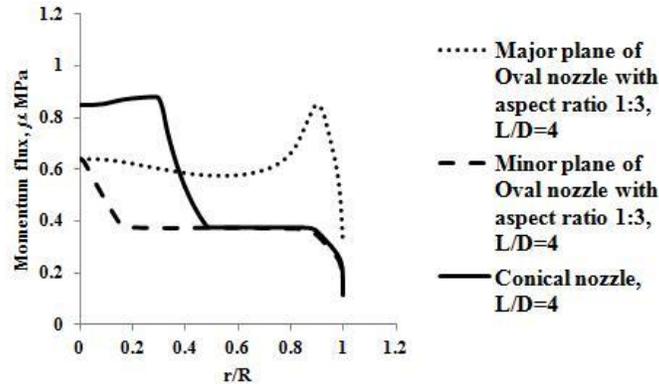


FIGURE 5. DISTRIBUTION OF MOMENTUM FLUX WITH A.R 1:3

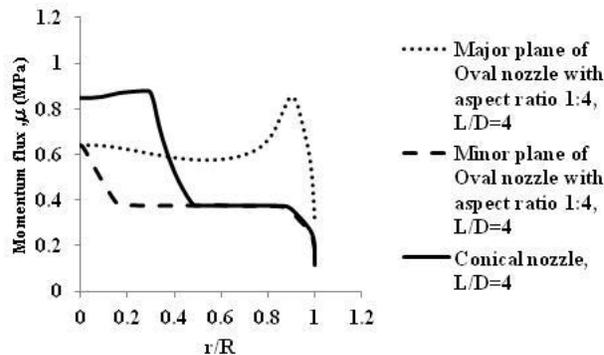


FIGURE 6. DISTRIBUTION OF MOMENTUM FLUX WITH A.R 1:4

7.2 DEGREE OF MIXING (DOM)

DOM gives direct measure of the mixing of the combined stream. There is a momentum gradient between primary and secondary streams. The variation of DOM based on numerical analysis for various configurations under Oval nozzles is shown in figure 7. It is evident from the figure that the value of DOM is appreciably high for Oval nozzles. This proves that Oval nozzle with aspect ratio 1:3 and 1:4 configurations achieves highest DOM in a three dimensional flow field, within a short mixing chamber when compared to conical configuration.

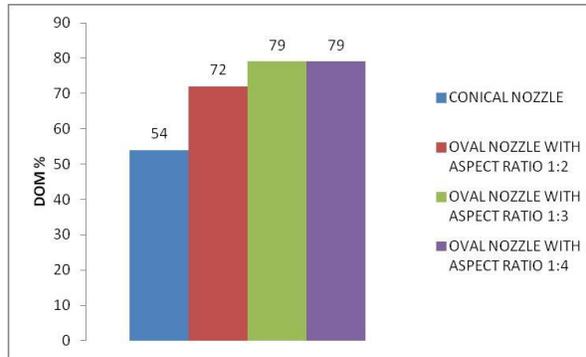


FIGURE.7 VARIATION OF DOM FOR OVAL AND CONICAL NOZZLE

7.3 PRESSURE DROP FACTOR

The PDF for various configurations are shown in figure 8. It is clear that pressure drop for Oval nozzles are higher than conical nozzle. From the DOM and PDF data the Oval nozzle with aspect ratio 1:3 and mixing chamber of $L/D=4$ configuration gives the better performance. The additional pressure drop of Oval nozzle with aspect ratio 1:3 and 1:4 can be attributed due to the following factors.

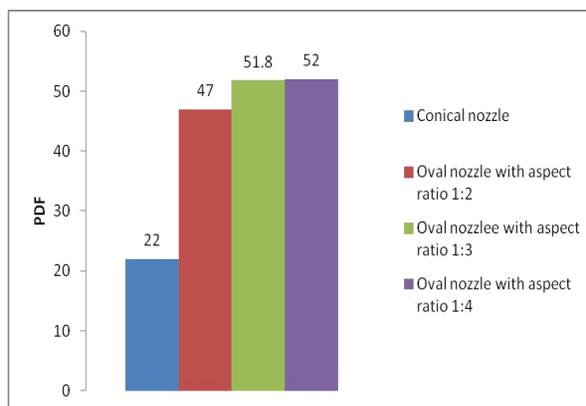


FIGURE 8. VARIATION OF PDF FOR OVAL AND CONICAL NOZZLE

1. Probable increased shock losses due to a decrease in minor axis infested flow field downstream of Oval nozzle.
2. Losses due to the enhanced mixing.
3. Due to increased surface area of the major plane of the nozzle, viscous losses are increased.

It is inferred that Oval nozzle by changing the aspect ratio i.e increasing the major diameter and decreasing the minor diameter gives better mixing. Among the Oval nozzles, 1:3 configuration is optimum.

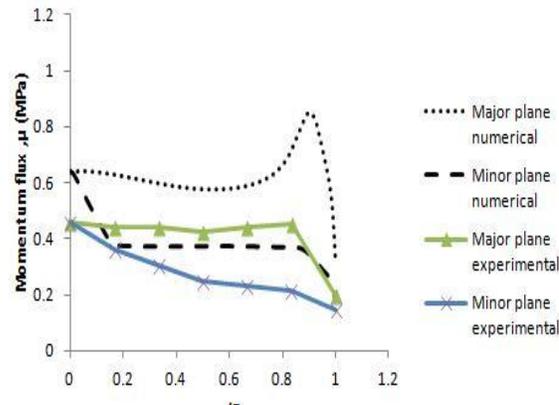


FIGURE 9. COMPARISON OF MOMENTUM FLUX AT MAJOR AND MINOR PLANE BETWEEN NUMERICAL AND EXPERIMENTAL RESULT OF OVAL NOZZLE WITH ASPECT RATIO 1:3, $L/D=4$

7.4 CONCLUSION

Numerical and experimental investigations were conducted in cold flow to investigate the mixing performance of Oval nozzle by changing aspect ratio in supersonic flow and also to compare the same with that of a conventional conical nozzle with same throat area and exit diameter. Major conclusions drawn from the study are highlighted below:

1. Oval nozzle with varying aspect ratio by increasing major diameter, momentum flux at major plane becomes flat by changing the aspect ratio, hence enhance the mixing.
2. The value of DOM showed that mixing achieved by Oval nozzle is better than conical nozzle. Oval nozzles with aspect ratios 1:3 & 1:4, $L/D=4$ showed highest DOM value 0.79.
3. Pressure drop factor for Oval nozzle configurations is more than that of conical configurations is indicates enhanced mixing and increased viscous losses.
4. The results are experimentally validated by comparing the theoretical momentum flux of oval nozzle with aspect ratio 1:3 with experimental data. The maximum and minimum deviation between the experiment and numerical results of momentum flux are 35 % and 20% respectively. This shows that a fair agreement with the theoretical assumption.

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