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Mixing Enhancement in Supersonic coaxial flows with angled rear wall cavity using clover nozzle

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Abstract— In hypersonic air breathing engines, due to the extremely short residence time of air in supersonic combustor, an efficient mixing between two coaxial streams is very hard to achieve. The overall issue is to enhance mixing in such engines, by introducing both active and passive mixing techniques. Active method by the introduction of cavities and passive method by using three lobed Clover nozzle. Numerical study of supersonic flow over cavity was carried out by varying the aspect ratio of the mixing tube and the rear wall inclinations of cavity inside the mixing tube. The mixing effectiveness in the various configurations was analyzed with the help of mixing parameters. The results indicated an enhancement in mixing and also the pressure losses were minimized when clover with rear wall inclined cavity configurations are employed.

Keywords- Cavity flow, Degree of Mixing, Mixing tube, Momentum flux, Pressure Drop Factor, Supersonic Mixing, Three lobed Clover nozzle.

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1 INTRODUCTION

Many experimental and numerical analysis have been reported during the last few decades regarding the characteristics of complex flow field resulting due to fuel air mixing and combustion. So there is a need to have efficient mechanism for fuel injection, fuel air mixing in short period of time with reduction in pressure loss. Earlier studies on flow over cavity were aimed at studying self sustained oscillations which are the source of flow noise and undesirable structural loadings. In the current decade the effect of flow over cavity due to cavity oscillations enhances the mixing and flame holding in supersonic combustors .In Hypersonic air-breathing propulsion devices such as Air Augmented Rocket (AAR) and Dual Combustor Ramjet (DCR) proper mixing of supersonic streams in a short mixing chamber plays an important role . In an AAR configuration as shown in fig.1, the combustion products from primary combustor of rocket which are typically fuel rich in nature, enters a secondary combustor in supersonic speed get mixed with atmospheric air induced through a converging air-intake and burns again to get additional thrust [1].

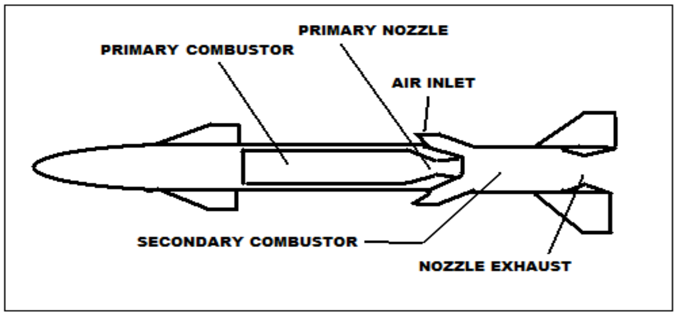

Fig. 1. Air Augmented Rocket (AAR)

On the other hand, in a DCR configuration as shown in fig.2, the air enters through a ramjet inlet and helps to burn fuel rich exhaust from primary chamber, in secondary combustor [2].

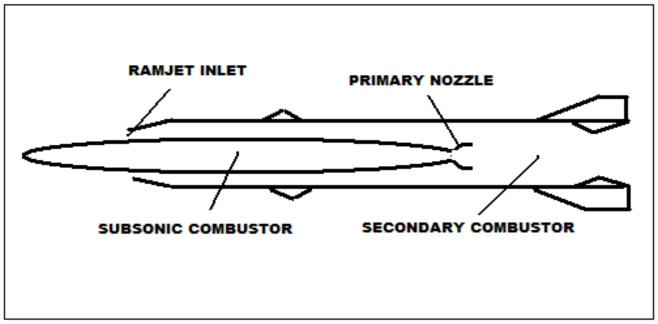

Fig. 2.Dual Combustor Ramjet (DCR)

BenYakar et al [3] discussed the need for optimal configuration of cavities that would yield the most effective flame holding capability with minimum loss. K M Kim et al [4] optimized by exploring various types of cavity configurations at a free stream Mach 2.5 to find the effective cavity based fuel injection system that leads to effective flame holding and combustion enhancement. In the Research of Tianwen FANG et al [5] the effect of cavites of different sizes on supersonic flow field were investigated experimentally and numerically and the results indicated that the L/D ratio within the range of 5-9 has little relevance to integral structure of the cavity flow. Also he found that the bevel angle of the rear wall does not alter the overall structure of the cavity flow within the range of 30^0-60^0, but it can exert obvious effect on the evolvement of shear layer and vortices in cavities. Gruber et al [6] experimentally and numerically studied the effect of flow over cavities with different aft wall angles and offset ratios. Although the study was done to identify potential configuration for flame holding, but the study was limited to low aft wall angle rectangular cavity. It is already known that the mixing can be enhanced by active and passive mixing techniques. In active mixing method, turbulence, shock

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interactions, swirls etc are introduced into the flow by active components like cavities, struts etc. On the other hand in passive mixing technique, the initial condition of jet is changed by altering the nozzle geometry. Different shapes like rectangular, elliptical, lobed etc have been assigned to the nozzles instead of conventional circular ones. These have been found to give better mixing as compared to conventional circular nozzle. In this context, it has been understood that externally imposed acoustic oscillations influence the compressible shear layer in a high speed jet and enhance mixing. The wall mounted cavities can generate this type of acoustic oscillations and hence the effect of cavities is considered in this study [1], [7]. Jayekumar and Balachandran [8] conducted an experimental study on mixing enhancement in supersonic streams with axisymmetric cavities. It was observed that wall mounted cavities enhance momentum mixing of two supersonic streams within a mixing duct. However the stagnation pressure loss was marginally increased for cavity configuration. Three lobed clover nozzle is introduced to add passive mixing. Studies towards this direction [9] showed that a clover nozzle, which is a class of radially lobed nozzle, provides better pressure recovery compared to normal lobed nozzle. It was also been proved experimentally [10], [11] that clover nozzle can enhance mixing of high speed jet stream at marginal stagnation pressure loss compared to conventional circular nozzle.

From the above literature survey it can be seen that the mixing enhancement with rear wall inclined cavity using clover nozzle has not been studied yet. In this study the effect of axisymmetric rear wall inclined cavity in the mixing tube along with clover and circular nozzle in coaxial supersonic streams is analyzed numerically by varying the aspect ratio of mixing tube and rear wall inclinations of cavity.

In order to compare the performance of clover nozzle and conical nozzle, both the nozzles were chosen so that the designed exit Mach number and throat area are the same. Clover nozzle is a convergent divergent nozzle where the nozzle cross section gradually changes from circular to lobed from throat to exit. The various configurations of nozzles and cavities are given in table 1. From these, the configuration that enhances mixing better was investigated.

TABLE 1
CONFIGURATIONS

Sl no.	Clover Nozzle (l/d=1.66)		Conical Nozzle (l/d=1.66)	
	L/D=4	L/D=5	L/D=4	L/D=5
1	θ=30°	θ=30°	θ=30°	θ=30°
2	θ=45°	θ=45°	θ=45°	θ=45°
3	θ=60°	θ=60°	θ=60°	θ=60°
4	θ=90°	θ=90°	θ=90°	θ=90°

2 DETAILS OF NUMERICAL ANALYSIS

2.1. Numerical analysis

A simple schematic diagram of numerical analysis configuration for circular nozzle with cavity is shown in fig. 3.

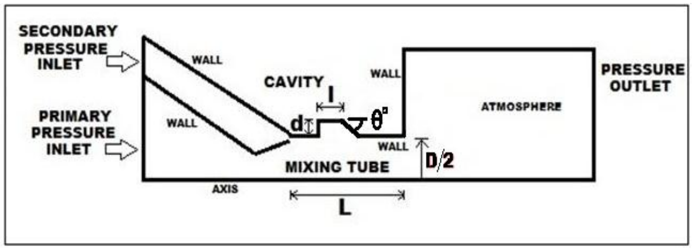

Fig. 3. Schematic diagram of circular nozzle configuration

In the case of circular nozzle, a two dimensional axisymmetric model was created, but for clover nozzle a three dimensional model was required due to its non-axisymmetric configuration at the exit plane. It was found that the three lobed clover nozzle exhibits symmetry about the major and minor plane such that the included angle between them is 600 as shown in fig.4. So 600 sector model is used to simulate, when primary nozzle is Clover.

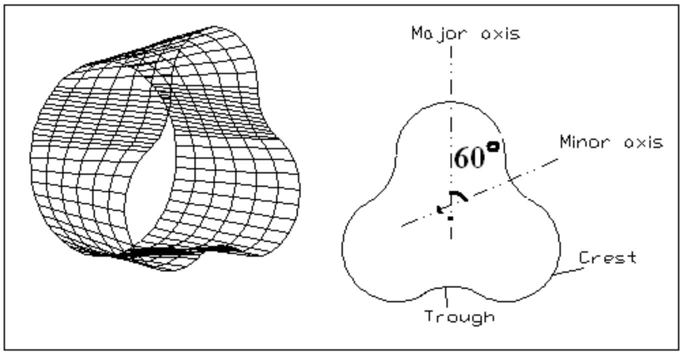

Fig. 4. Three lobed Clover nozzle

Numerical analysis was done by using commercial software FLUENT 6.3.26. For circular nozzle, an axisymmetric model was used with structured grid system having quadrilateral cells as shown in fig. 5.

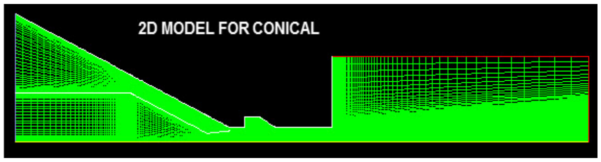

Fig. 5. Grid system for Conical nozzle L/D =4, l/d = 1.66 @30° rear wall inclined cavity

For Clover nozzle, the sector discussed earlier was selected. The grid system consists of hexahedral cells as shown in fig.6. For primary nozzle, pressure inlet boundary condition is 10 bar, 300K was imposed at primary inlet. For secondary nozzle, pressure inlet condition was given as 2 bar and 300K. Pressure outlet condition with atmospheric properties (300K and 1.01325 bar) set at outlet. Analysis in both cases were done using k-ω turbulence model with coupled implicit solver.

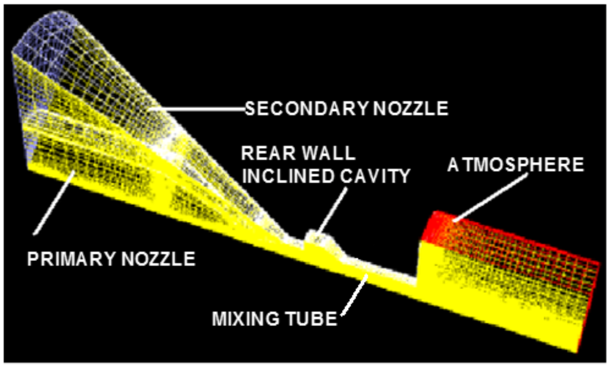

Fig. 6. Grid system for Clover nozzle L/D =4, l/d = 1.66 @30° rear wall inclined cavity

Sixteen cavity models for two mixing tubes of L/D=4 & L/D=5 using clover and conical nozzles were analyzed. The constant length to depth ratio of 1.66 with different aft-wall inclinations (θ) used in the cavity shown in fig.7. The cavity dimensions in the present study are summarized in Table 2.

TABLE 2
CONFIGURATIONS

Sl No	Length l (mm)	Depth d (mm)	l/d	Effective Length Le(mm)	Aft-wall Angle θ°
1	10	6	1.66	20.39	30
2	10	6	1.66	16.0	45
3	10	6	1.66	13.46	60
4	10	6	1.66	10.0	90

The effective length 'Le' as shown in fig.7 is defined as the distance from the leading edge to the trailing edge.

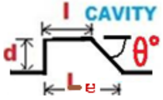

Fig. 7.Schematic of rear wall inclined cavity

3 DEFINITION OF MIXING PARAMETERS

3.1 Momentum flux (μ)

The coaxial jets enter into the supersonic combustor with different momentum and stagnation pressures. The momentum flux distribution at the exit of the supersonic combustor in the radial direction is the measure of bulk mixing. Momentum flux is calculated as,

$$\mu = p\,(1+\gamma\ M2)$$

where p is the static pressure and M is the Mach number calculated from measured values of stagnation pressure. The momentum flux at which uniformity is attained indicates the axial distance where mixing is complete. In the Clover nozzle, momentum distribution was studied at major and minor planes.

3.2 Degree of Mixing (DOM)

To make a comparison between the mixing performance of clover and circular nozzle for different cavities based on a quantitative assessment of the level of mixing achieved, a dimensionless parameter called uniformity factor Φ is defined as

$$\Phi = 1-[\sigma_{\mu}(x)/\ \mu_{av}(x)]$$

where σμ (x) is the standard deviation of the radial distribution of momentum flux at a given axial location along the mixing tube. μav (x) is the average of momentum flux along a radial line at the location considered. This factor is a measure of the uniformity of the momentum flux distribution in the radial direction, at a given location. For a perfectly mixed flow, the distribution has to be uniform across the section. The uniformity factor is used to define a mixing parameter called the Degree of Mixing (DOM).

$$DOM = (\Phi - \Phi_{UM}) / (1- \Phi_{UM})$$

where ΦUM is the values of Φ when the two streams are totally unmixed and DOM will be zero.

3.3 Pressure Drop Factor (PDF)

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

$$PDF = 1-\left(P_{0E}/P_{OI}\right)$$

where,

$$P_{0I} = (P_{0P}\times A_P + P_{0S}\times A_S)/(A_P + A_S)$$

where P0I and P0E are the area weighted average of total pressure at the supersonic combustor inlet and exit.

4 RESULTS AND DISCUSSION

4.1 Radial distribution of momentum flux (μ)

Figure 8, 9, 10 and 11 shows the radial distribution of momentum flux at the exit of mixing tube of L/D =4 with various rear wall inclinations. r/R denotes the radial distance from the axis(r) normalized by radius of the mixing tube(R).

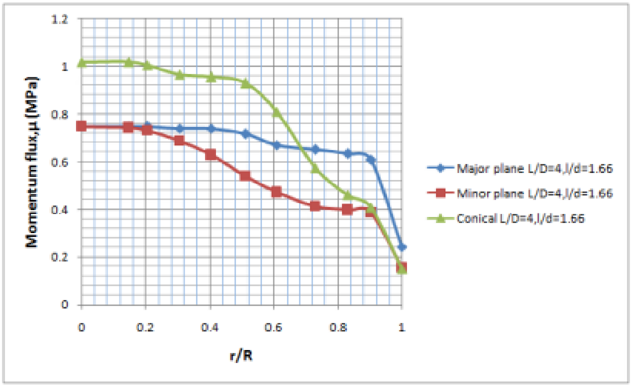

Fig. 8. Radial distribution of momentum flux in L/D = 4 [l/d=1.66, @30º rear wall inclined cavity] mixing tube

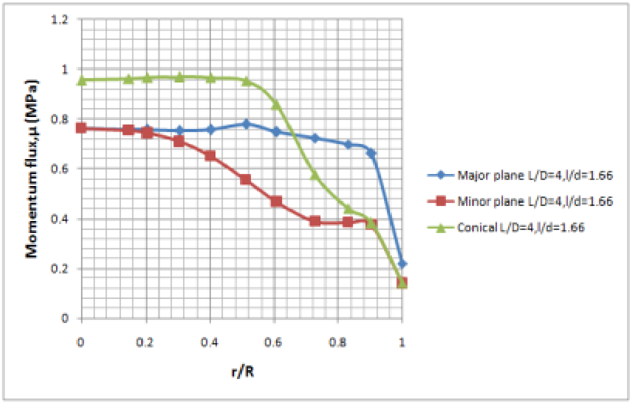

Fig. 9. Radial distribution of momentum flux in L/D = 4 [l/d=1.66, @45º rear wall inclined cavity] mixing tube

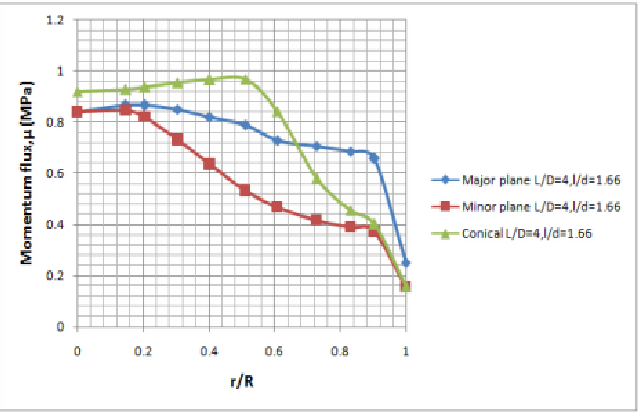

Fig. 10. Radial distribution of momentum flux in L/D = 4 [l/d=1.66, @ 60º rear wall inclined cavity] mixing tube

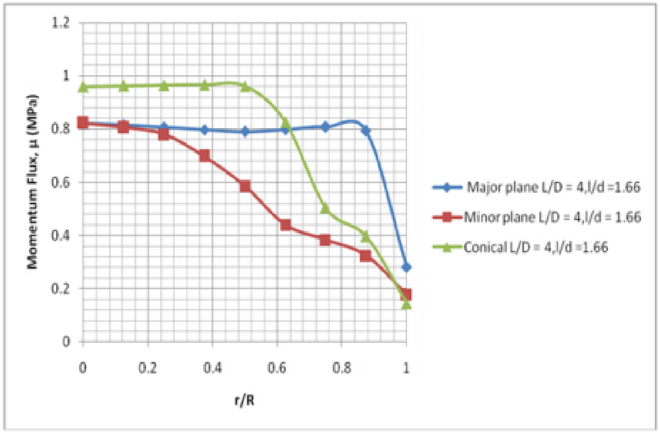

Fig. 11. Radial distribution of momentum flux in L/D = 4 [l/d=1.66, @ 90º rear wall inclined cavity] mixing tube

Figure 12, 13, 14 and 15 shows the radial distribution of momentum flux at the exit of mixing tube of L/D =5 with various rear wall inclinations when three lobed clover/conventional conical nozzle is used as the primary nozzle.

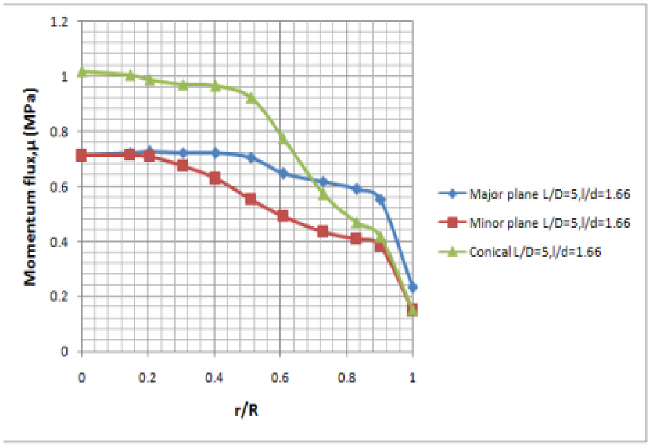

Fig. 12. Radial distribution of momentum flux in L/D = 5 [l/d=1.66, @ 30º rear wall inclined cavity] mixing tube

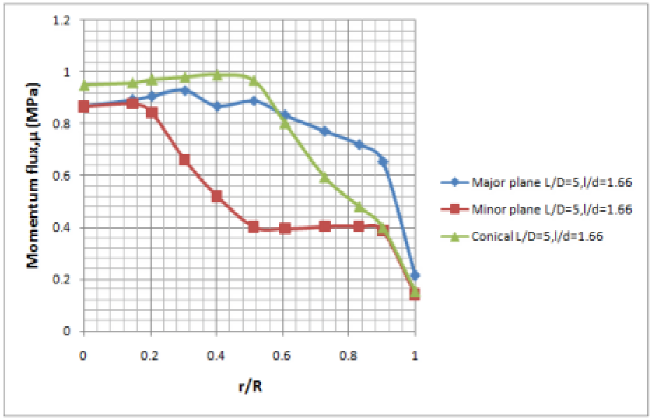

Fig. 13. Radial distribution of momentum flux in L/D = 5 [l/d=1.66, @ 45º rear wall inclined cavity] mixing tube

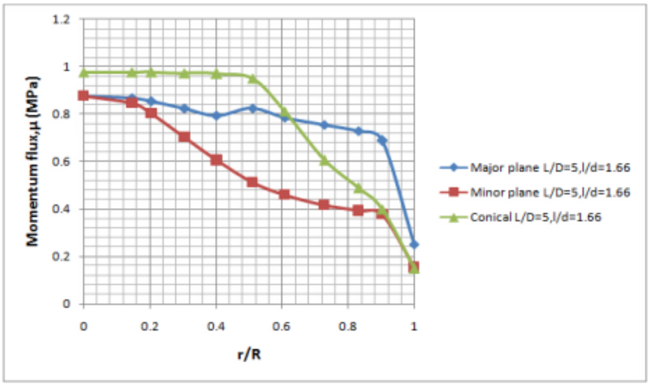

Fig. 14. Radial distribution of momentum flux in L/D = 5 [l/d=1.66,@ 60º rear wall inclined cavity] mixing tube

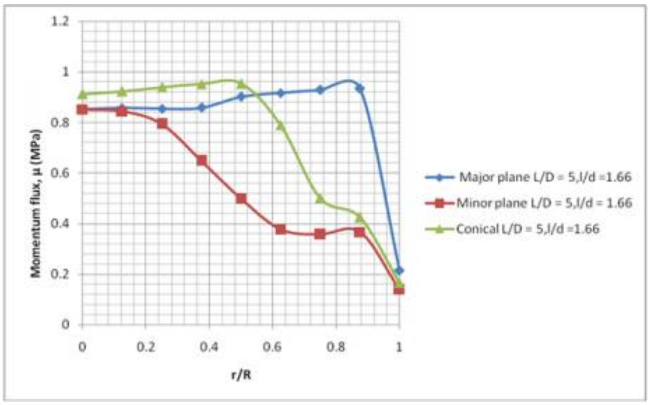

Fig. 15. Radial distribution of momentum flux in L/D = 5 [l/d=1.66, @ 90º rear wall inclined cavity] mixing tube

In the case of Clover nozzle, the primary stream that possesses higher momentum, issues along the lobe region. The secondary stream having lower momentum issues through the inter lobe region that is centered along the minor plane. For conical nozzle the momentum distribution continues to be non uniform in all configurations, where as it becomes progressively uniform when Clover nozzle configurations are used. From figures 8, 9, 10, 11, 12, 13, 14 & 15, in case of conical configuration as r/R is increasing from 0.5 the curve shows a drop which indicates poor mixing between primary and secondary streams. Moreover the momentum flux values near wall (r/R = 1) is lower when compared to Clover configurations. This indicates that Clover nozzle with cavity enhances mixing.

From the figures 8 & 12 it is evident that L/D = 4, l/d = 1.66, @ 30º rear wall inclined cavity and L/D = 5, l/d = 1.66, @ 30º rear wall inclined cavity gives a more uniform momentum flux distribution when compared to other configurations and the former has a slight edge over the latter.

4.2 Degree of Mixing

Fig.16 compares the variation of DOM for various configurations under Clover and conical nozzles. It is evident from the figure that the value of DOM is appreciably high for Clover with rear wall inclined cavity configurations when compared to others.

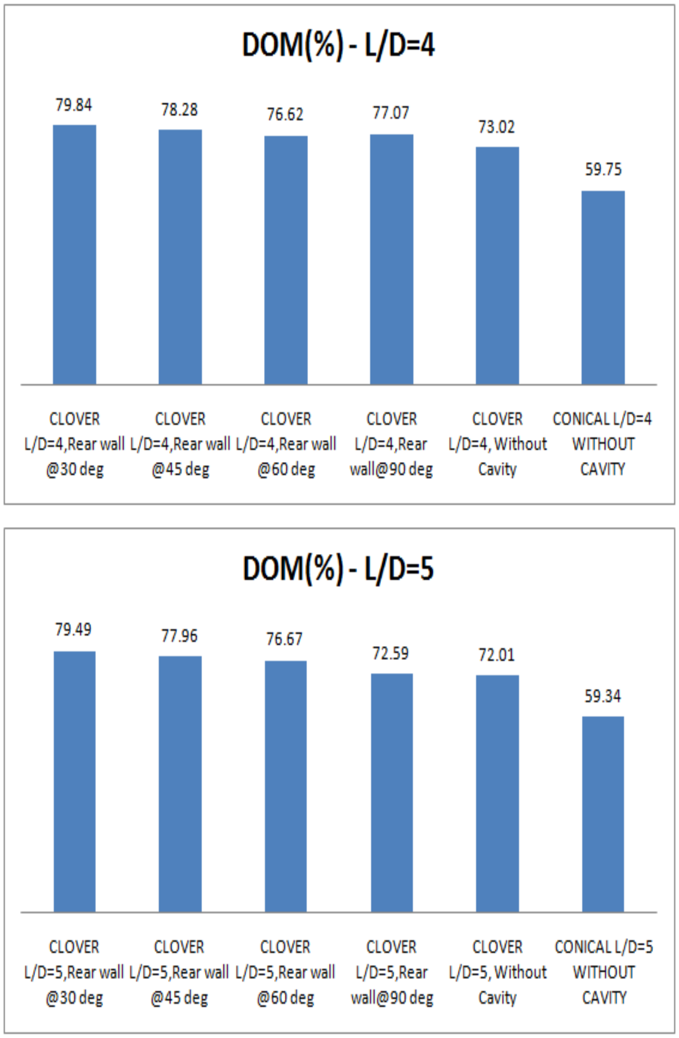

Fig. 16. Comparison of DOM [L/D=4 Vs L/D=5]

This proves that Clover nozzle with cavities configurations achieves nearly complete mixing in a three dimensional flow field, within a short mixing chamber when compared to conical configurations. Compared to other configurations Clover L/D = 4, l/d = 1.66, @ 30º rear wall inclined cavity shows highest DOM.

4.3 Pressure Drop Factor (PDF) in configurations.

The PDF for various configurations are showed in fig. 17. The increased pressure drop in the case of Clover nozzle with cavity configurations is clearly seen. This additional pressure drop is more predominant at larger L/D. In general, by providing rear wall inclined cavity in the mixing tube helps to reduce the pressure drop and to enhance the mixing when compared with corresponding rectangular cavity.

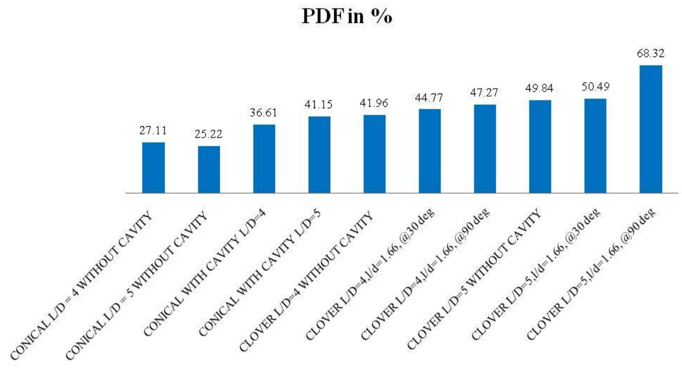

Fig. 17. Comparison of PDF

The additional pressure drop in the case of Clover configurations can be attributed due to the following factors.

1. Probable increased shock losses due to a complex shock infested flow field downstream of lobed nozzle and the cavity.
2. Losses due to the enhanced mixing.
3. Due to increased surface area of the nozzle, the viscous losses are increased.

The major inference from the above study is that Clover nozzle with rear wall inclined cavity gives better mixing compared to other configarations. Results indicated that Clover nozzle with L/D = 4, [l/d = 1.66, @ 30º rear wall inclined cavity] mixing tube is the best configuration for effective mixing.

5 CONCLUSION

Numerical investigations are conducted in cold flow to investigate the mixing performance of Clover nozzle with rear wall inclined cavity in supersonic flow and also to compare the same with that of a conventional conical nozzle with rear wall inclined cavity. Major conclusions drawn from the study are highlighted below:

a) Clover nozzle with rear wall inclined cavity provided better mixing in three dimensional supersonic flow field inside a comparatively short mixing chamber. In the present study, the configurations L/D = 4, l/d = 1.66, @ 30º rear wall inclined cavity and L/D = 5, l/d = 1.66, @ 30º rear wall inclined cavity gave flat momentum flux distribution in the radial direction at the end of the mixing tubes.

b) The value of Degree of Mixing showed that mixing achieved by Clover nozzle with rear wall inclined cavity is better when compared with other configurations. L/D = 4, l/d = 1.66 @ 30º rear wall inclined cavity showed highest DOM value of 0.8599 along major plane.

c) By using clover nozzle with L/D = 4 [l/d = 1.66, @ 30º rear wall inclined cavity] and L/D = 5 [l/d = 1.66, @ 30º rear wall inclined cavity] mixing tubes, the % reduction in PDF are 5.28 and 26% respectively as when compared with corresponding rectangular cavity. The Pressure Drop Factor associated with Clover configurations is more than that of conical configurations is due to enhanced mixing and increased viscous losses.

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SCOPE FOR FUTURE WORK

Experimental investigation is to be done inorder to validate the numerical results. A study of flow structure issuing from the clover nozzle and in the rear wall inclined cavity, is needed for further explanation on the shock structure. This can be achieved with the help of Schleiren system. Flow visualization studies can also be made.to analyse the vortices formed near lobe region and in the rear wall inclined cavity.

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