Effect of Lobe Angle of Clover Nozzles on Coaxial Supersonic Streams

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Abstract

Radially lobed nozzles are widely accepted as a means of enhancing the mixing of two supersonic streams. In the present work, an experimental investigation on the effect of lobe angle of clover nozzle, a new type of radially lobed nozzles, in confined supersonic mixing has been carried out. The nozzles are designed to operate at Mach 1.5.The experimental set up consist of a primary chamber to which the design nozzles are attached and a secondary chamber to which a convergent cone is attached to produce Mach 1.Stagnation pressure readings are taken radially along the major and minor planes downstream of clover nozzle. The radial measurements are taken at different axial positions from exit plane of the nozzles. Mach number distribution, stagnation pressure loss and momentum flux distribution across the radial direction of nozzle at different axial locations are found out and compared with a conventional conical nozzle of same throat diameter and operating conditions. These results showed the influence of lobe angle on stagnation pressure loss and mixing enhancement. It is observed that the mixing enhancement not only depend on lobe angle but also on the number of vortex generating planes. It was also found that increase in lobe angle produces more pressure loss. These results emphasize that neither pure shear mixing nor vortex mixing alone is responsible for the mixing of coaxial supersonic streams. An optimum balance between both is required for a better mixing with minimum loss within in a short span.

1. Introduction

The proper mixing of supersonic streams plays an important role in advanced propulsion systems such as air augmented rockets and dual combustion rockets and in supersonic ejectors. In air augmented rockets, the mixing of intake air with the primary rocket exhaust in proportions which enables the propulsion device to retain the characteristics of typifying a rocket. In air breathing scram jet engines, the atmospheric oxygen will mix with fuel to propel the vehicle. This requires a secondary combustion chamber in which the hot fuel rich gases from the primary rocket nozzle get mixed and burns with oxygen in the air supplied by the air intake system. The supersonic stream from primary nozzle must mix thoroughly and react with coaxial stream with in a short span.

The major technical problem to be solved in many of these applications is the thorough mixing between two gaseous supersonic streams. Uniform mixing of fuel and oxidant at the correct rate have major influence on the efficiency of combustion and heat release rate. The mechanism of mixing of two coaxial streams depends on the growth of shear layer between two streams. In circular nozzle, jet mixing is promoted purely by shear layer mixing. Since growth of shear layer is controlled by compressibility factor at supersonic speeds as explained by Papamoschou.D. and A.Roshko. [1], it is difficult to achieve proper mixing between two high speed streams in a short mixing chamber if a circular nozzle is obtained. To reduce the length of secondary combustion chamber, rapid mixing between the hot gases and air is essential. This drawback can be sorted to certain extend with vortex generation in co-flowing streams. Tillman [2] investigated and highlighted the mixing enhancement of compressible jets using forced mixer nozzles. In this study they found that the mixing mechanism of a lobed nozzle is characteristically different from that of a conventional nozzle. In the case of jets from circular nozzles mixing is dominated by momentum transfer through the action of viscous shear stresses and small scale turbulence in the mixing layer. Hence the slow growth rate of supersonic shear layers renders the conical nozzle highly inefficient for applications involving supersonic mixing. A rectangular nozzle provides better mixing than a circular nozzle of same exit area owing to the distribution of viscous shear stresses over a larger surface area. The jet mixing was characterized by measured distribution of total temperature, total pressure, static pressure and velocity. The study revealed that the generation of large scale vortex structures was effective in the mixing of supersonic jets. Another method of enhancing mixing was by introducing cavities in combustion chamber. Jeyakumar.S and Balachandran.P [3] experimentally conducted a study in supersonic stream with axisymmetric open cavities of different length to diameter ratios with dual supersonic flow over cavity configurations. The stagnation pressure loss was marginally increased compared with no cavity configuration. The planar Mie scattering pictures indicates qualitatively that the cavities contribute to the mixing enhancement of supersonic stream.

Recent studies had been more on radially lobed nozzles and forced mixers. Anil and Damodaran [4] studied the mixing characteristics of petal nozzles (a type of radial nozzle) in coaxial supersonic streams. The result revealed that momentum transfers in radial direction is more rapid compared to an equivalent convergent divergent nozzle. The experiment also included study on thermal mixing. A uniform temperature profile was attained at l/d=4.25.A quantitative analysis of mixing and stagnation pressure drop of petal nozzles was done by Job Kurien[5].The experiment confirmed the superiority of petal nozzle in enhancing mixing to conical nozzle. A complete mixing of momentum was obtained at l/d=4.44 for a six lobed nozzle. But the stagnation pressure drop was more due to shock loss.

All these studies stated that the mixing enhancement of radially lobed nozzles is due to the stream wise vortices, in addition to vortices formed in axisymmetric shear layers. Further studies on lobed nozzles were concentrated on the mixing mechanisms and the factors which influence the mixing efficiency. V.M.Belovich [6] conducted an experimental investigation to study the effect of various parameters such as the interfacial area increase due to lobed geometry and the strength of stream wise vortices, on the mixing processes. Results showed highly enhanced mixing as the strength of the stream wise vortices increased due to increased interfacial contact area. The strength of vortex generated in a lobe depends not only on initial flow conditions but was more dependent on the geometrical conditions. This was suggested by Simon.C.M. [7] from his study of velocity and turbulence characteristics of a lobed-forced mixer with three different trailing edge configurations having shape of square, semicircular and triangular. Also, in lobed mixers, mixing enhancement was done greatly by the formation and interaction of the azimuthally and stream wise vortex [8].This was in agree with the studies of D.C.McCormick [9]. He confirmed the existence of normal vortex which sheds periodically from convoluted trailing edge of lobed mixer and plays an important role in enhancing mixing process. The velocity difference between co flowing streams also plays an important role for maximum mixing enhancement.

Recently a new type of nozzle, clover nozzle which is a modified form of lobed nozzle was experimentally studied by Swaraj etal [10]. It differs from petal nozzle in the view that sharp corners are avoided providing a wavy profile for the lobes. It showed that clover nozzles improve mixing compared to conical nozzle without much pressure loss. He studied the mixing performance of a four lobed and six lobed clover nozzles and compared with that of conventional conical nozzle in coaxial isothermal supersonic streams. The quantitative analysis of the uniformity in momentum distribution showed superiority of mixing performance of clover nozzle that of conventional conical nozzle. The mixing approached almost uniform profile at l/d=4and was completed at l/d=7 for four lobed nozzle.

In the present study an attempt has been made to study the effects of lobe angle of clover nozzle on its mixing performance and compared the results with a conventional convergent divergent (CD) conical nozzle. The nozzle tested is designed to operate at a pressure ratio of 4:1.Four types of clover nozzles having 3,4,6,8 lobes are tested. From the stagnation pressure measurements along the major and minor planes of clover nozzles, momentum distribution is calculated. The study of momentum distribution profile helped to assess the axial distance required for complete mixing. The results showed that the momentum distribution along the radial direction is more rapid compared to an equivalent CD nozzle. The effect of lobe angle on mixing mechanism of clover nozzles is also suggested. It is found that lobe angle is a strong factor in controlling the generation of vortices. The variation of degree of mixing with lobe angle pointed out that the mixing effectiveness of nozzles is not varying linearly with lobe angle but there is an optimum lobe angle which promotes better mixing. It is found out that further increase in lobe angle results in more stagnation pressure loss. From this it is concluded that vortex generation alone cannot result in mixing of coaxial supersonic streams but an optimum balance between shear mixing and vortex generation is required.

2. Experimental Technique

2.1 Test Facility

The facility used to carry out experiments consists of air supply system and the test setup including nozzles and instrumentation. The air supply to the primary and secondary chamber was given separately from two compressors. The compressors are two stage two cylinder air cooled reciprocating type compressor with intercooler. The working pressure of primary compressor is 1.2 MPa with free air delivery of 700 litre/minute and the working pressure of secondary compressor is 1.2 MPa with free air delivery of 500 litre/minute from their respective storage tanks. The air supplied to the primary and secondary chamber through a 1 inch pipe line consisting of gate valve, orifice meter, pressure gauges and pressure regulator. The pressure regulator from the compressor regulates the air pressure to 0.4MPa and 0.2MPa in primary chamber and secondary chamber respectively. Even though the mass flow rate is constant due to choked flow in the nozzle, orifice meter is mounted in the flow lines for confirmation. The facilities are designed such that maximum Mach number in the air supply line doesn't exceed Mach 0.1.The experimental setup employed is shown in Figure 1. The primary nozzle is connected to the primary chamber (l=60cm, d=6cm) and the secondary conical convergent nozzle is connected to the secondary chamber (l=31cm, d=15cm).Provisions are made in the flanges of both chambers to attach the nozzles. Both nozzles are tightened by placing gaskets in between the flange and nozzle such that the exit planes of two nozzles are same. The secondary nozzle which is attached to secondary chamber have 2mm gap between the peaks of each lobe and the inner wall of secondary nozzle. The exit pressure is made (0.11MPa) slightly higher than atmospheric pressure.

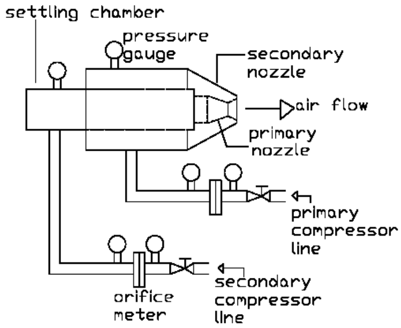

Figure 1 : Schematic representation of test setup

The primary and the annular secondary flow mix within the mixing chamber located downstream of the nozzles. The mixing chamber used down stream is replaceable brass pipe of variable lengths. The need of variable length is to take measurements at different l/d (length/diameter) ratios. The pressure in the major and minor plane was measured using a calibrated pressure probe mounted on a three dimensional traversing mechanism having a movement accuracy of ±0.1mm. The probe is connected to the digital manometer of accuracy ±3% of full scale at 25^0C. The area blockage due to introduction of the pressure probe is 0.54%.All the measurements were carried out at room temperature of 30±2^0C.

2.2 Experimental Procedure

Air from the receiver tanks of compressors is fed to the primary and secondary chamber. The pressure regulators are regulated in such a way that pressure in primary and secondary chamber is 0.4MPa and 0.1MPa respectively. The upstream and downstream pressure readings in the pressure gauges are noted as the air flows through the nozzle. The pressure at the nozzle exit is measured by pressure probe, which is attached to 3 dimensional traversing mechanism. The probe is connected to a digital manometer, which gives the stagnation pressure after the shock. Since the conical nozzles are symmetrical, measurements can be taken in any radial direction. In the case of the clover nozzles measurements are taken along major and minor planes. The measurements are carried out at l/d ratios of 1, 2, 3, 4, 5,6and7.The axial distance for measurement is varied by connecting mixing tubes of various lengths at the exit plane of nozzles. The same procedure is repeated for all nozzles. The total pressure values obtained after the curved shock was used to calculate the flow Mach number and momentum distribution of the supersonic stream.

2.3 Clover Nozzles

Clover nozzles are radially lobed nozzles. Two principal planes are identified in the flow field downstream of clover nozzles (Figure2). The plane that bisects the region with crest is referred as major plane. Similarly the plane that bisects the trough is referred to as minor plane. The pressure readings are taken radially along major and minor plane. The angle between major and minor plane of each lobed nozzle is given below in Table 1.Figure 3 shows the dimensions of three lobe clover nozzle. The terminology lobe angle used in the present context is the angle between the upper lobe and lower lobe of clover nozzles. The conical plane at diverging section of circular conical nozzle is taken as reference. When lobe angle is zero, it refers to circular conical nozzle. The angle at which upper lobe and lower lobe deviate from this diverging plane can be termed as upper lobe angle and lower lobe angle respectively.

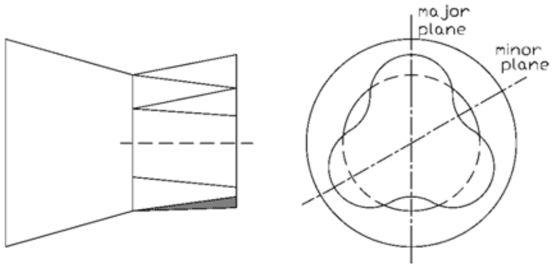

Figure 2:Major Plane and Minor Plane of Clover Nozzle

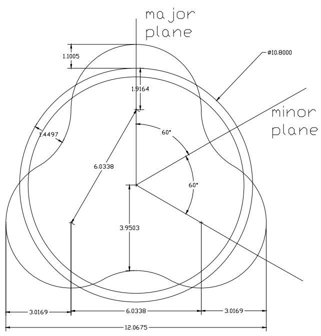

Figure 3 : Three lobe clover nozzle. Figure 4 :Clover Nozzles

Table 1: Angle between major and minor plane.

Number of Lobes	Angle between major and minor plane(degree)
3	**60**
4	**45**
6	**30**
8	**22.5**

Table 2: Lobe angle of clover nozzles.

	3 lobe	4 lobe	6 lobe	8 lobe
Lobe Angle(degree)	14	12	8	6

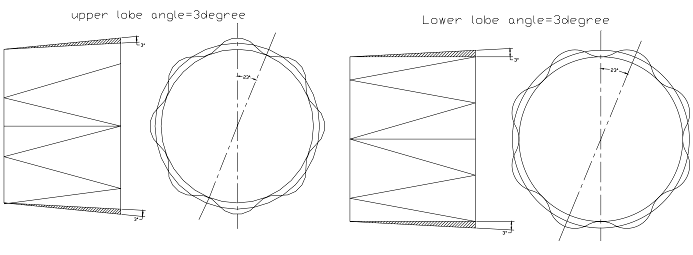

Figure 5:Upper and Lower lobe angle of 8 lobed clover nozzle.

The Figure 5 shows both angles of an eight lobed nozzle. Here the angle between the upper lobe and diverging plane is 3degree. Similarly the angle between lower lobe and diverging plane is 3 degree. Hence the lobe angle of an eight lobed clover nozzle is 6 degree. The lobe angle indicates the depth of waviness. The Table 2 shows lobe angle of all clover nozzles used in experiment.

3. Results and Discussions

3.1 Momentum Mixing with Clover and Conical Nozzles

To find out the axial distance at which mixing is near complete, the momentum flux distribution of each lobed nozzle is compared with that of conical nozzle. Measurements along the radial lines in major and minor planes of the clover nozzles are used to find extend of mixing in the transverse planes. Due to the geometry of clover nozzle the flow pattern in all segments of the nozzle will be similar. Figure 6, 7, 8, 9, shows the momentum flux along the major and minor plane of 4 set of clover nozzles at different l/d ratios.

A comparison of the momentum flux along the major and minor plane reveals that at downstream l/d ratios, a clear distinction exists between the momentum flux in two planes. The primary stream that possesses higher momentum occupies more transverse length along the major plane due to the presence of outward lobe. The secondary stream, having lower momentum, occupies more length in minor plane, due to the presence inner lobe. At low l/d, the two streams retain their identity and there is no appreciable mixing between two.

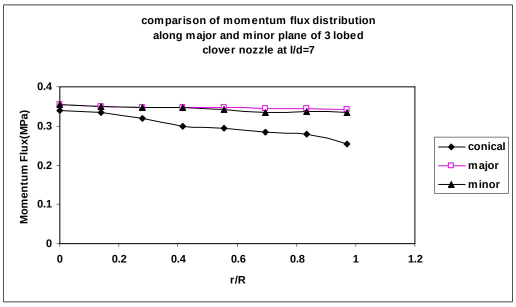

Figure 6

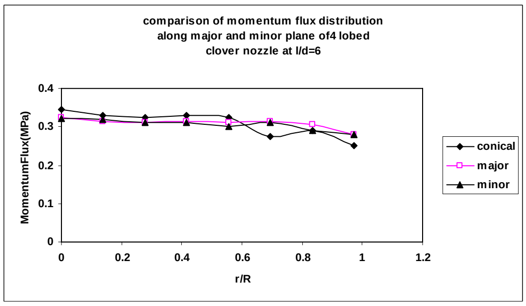

Figure 7

For three lobed nozzle, at l/d=5, it is seen that momentum profile started approaching uniformity. At l/d=7, the three lobed nozzle attain complete uniformity. Considering the uniformity in momentum as extend of mixing, we can say that nearly complete mixing between the two streams has occurred at this distance. Similar to this four lobed nozzle attains complete mixing at l/d=6.

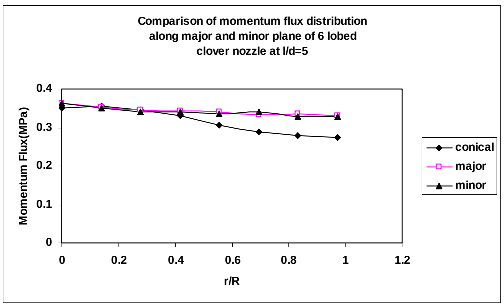

Figure 8

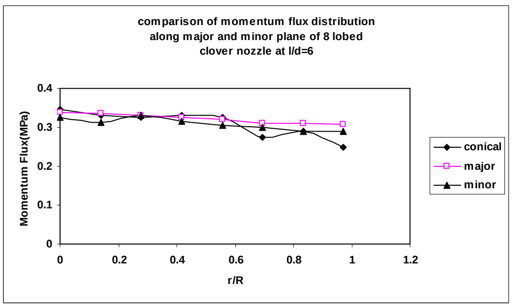

Figure 9

The six lobed nozzle mixes at a faster rate compared to three and four lobed nozzle. The mixing is nearly complete at an l/d=5.In eight lobed nozzle the mixing distance again increases to l/d=6. It can be interpreted that six lobed nozzle achieves faster mixing compared to other nozzles within short span.

3.2 Influence of Lobe angle on mixing enhancement

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

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

where $\sigma_{\mu}(x)$ is standard deviation of the radial distribution of momentum flux at a given axial location along the mixing tube. μ_{av} (x) is the average of momentum flux along radial line at the location considered. This factor is basically a measure of the uniformity of the flux distribution in the radial direction, at a given axial location. As there exist a momentum gradient between the primary and secondary streams, an unmixed flow field will be severely non-uniform in the radial direction, showing a higher momentum across the primary region and lower momentum across the secondary region. The standard deviation in the definition of Φ represents non uniformity at the given section. For a perfectly flat momentum profile Φ will be unity. The uniformity factor may be used to define a mixing parameter called Degree of Mixing (DOM).

$$DOM= (\Phi-\Phi_{UM})/ (1-\Phi_{UM}) \quad (2)$$

where Φ_{UM} is the value of Φ when the two streams are unmixed .This parameter, DOM gives a direct measure of the mixedness of the combined stream. It can be seen that when the two streams are completely mixed, DOM will be equal to zero. This parameter is used for comparing extend of mixing achieved by the four types of nozzles as shown in Figure10. When assessing the results of all the 4 set of nozzles with that of conical nozzles, the capability of enhancing the mixing by lobed nozzles is again confirmed. The mixing in conical nozzle is yet to be completed. The momentum profiles of major plane and minor plane of all set of nozzles at l/d=0 is same because the effect of nozzle wall waviness starts only at some distance away from the exit plane of the nozzles.

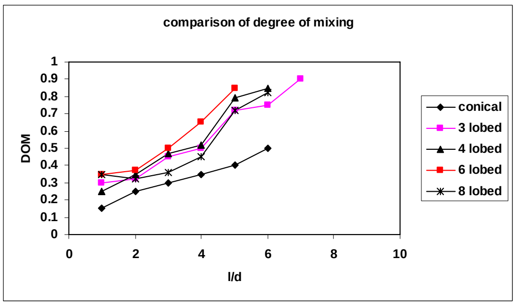

Figure 10

Among the lobed nozzles, six lobed nozzle showed better mixing within a short distance. This clearly indicates that the trend of mixing depend not only on the number of lobes. Studies already proved that mixing doesn't strongly depend on initial flow conditions but on geometrical profile of lobed mixers which refers to flow redirections occurring to streams [7]. The flow redirection in case of clover nozzles is controlled by the lobe angle. The outward lobe will be redirecting the flow outward while the inward lobe makes it inwards. When two parallel streams are diverted in this mode, a low pressure region is formed in between the major plane and minor plane. Some of the fluid particles moving outward will have a tendency to migrate to that low pressure region and simultaneously, the fluid particles from inward stream also move in. This creates a circulation which gradually develops into vortices. These vortices promote mixing. Figure 11 shows throat and divergent portion of three lobed clover nozzle. It represents the flow redirection and formations of vortices in between the major and minor plane. It can be considered that the vortex formation is neither in major plane nor in minor plane but in between both planes. This plane can be called as vortex generating plane, the plane where mixing is getting facilitated. But it cannot be concluded that the mixing depends only on lobe angle.

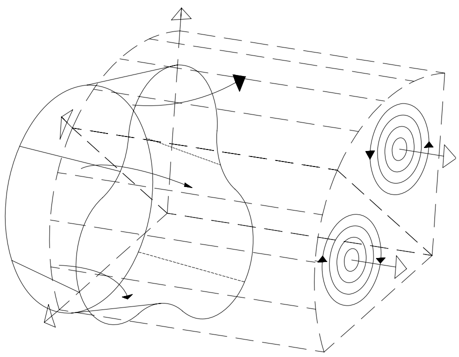

Figure 11 :Vortex formation in clover nozzle

Table 3: Lobe Angle and Vortex Generating Plane of Clover Nozzles

	3 lobe	4 lobe	6 lobe	8 lobe
Lobe Angle(degree)	14	12	8	6
Number of vortex generating planes	6	8	12	16

In clover nozzles, the lobe angle is different for all the nozzles. The variation in lobe angle indicates the change in number of lobes as well as change in lobe size. The experimental results showed that neither the three lobe (maximum lobe angle) nor the eight lobe (minimum lobe angle) showed better mixing. The six lobed clover nozzle showed complete mixing at a lesser span when compared to other nozzles. This indicates that some other factor must be changing as the angle changes which affect mixing effectiveness. When considering all the 5 set of nozzles, except the number of lobes, all other parameters (exit area, axial length of diverging portion) are same. For the same exit area, as the lobe angle increases, the lobe size increases, but the number of lobes decreases. Simultaneously, the vortices generating planes, mentioned earlier, also decreases. Table 3 shows the lobe angle and number of vortex generating planes of clover nozzles.The lobe angle and vortices generating planes are not directly proportional for same exit area. But both are key factors in facilitating mixing. An optimum balance is required between both factors to have a better mixing. Such an optimum balance between these factors is obtained in case of the six lobed clover nozzle, hence it shows a complete mixing within a short span.

3.3 Pressure Drop with Clover Nozzle

The stagnation pressure lose of clover nozzle was quantitatively assessed by a parameter called Pressure Drop Factor (PDF) defined in [6].The stagnation pressure loss for both primary and secondary flow is different. Hence (PDF) is defined as the difference between the weighted stagnation pressure at the inlet and the axial station considered, normalized by the weighted average of the inlet stagnation pressure. The weighted averaging of any quantity in the axisymmetric flow field by the conical nozzle is trivial, but it is not so in the case of the non axisymmetric flow field in the mixing chamber of the clover nozzle. For solving this problem of clover nozzle is considered to be symmetric with respect to an angular segment bounded by adjacent major and minor plane. The angular difference between major and minor plane is different for each clover nozzle as shown in Table 1. The weighted averaging of the data corresponding to each radial location is first done between major and minor plane of each nozzle. The resulting average value is used to compute the weighted average of the entire section.

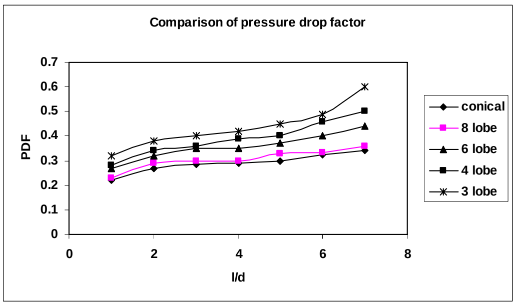

Figure 12

The Figure 12 shows the pressure drop of each nozzle at different l/d. The trend goes in accordance with the earlier study that pressure drop of clover nozzle is high when compared to conical nozzle. The pressure losses here can be due to complex shock interferences, enhancement in mixing and frictional losses. The six lobe clover nozzle attains a complete mixing at l/d=5.Figure13 shows that the pressure loss at this point is about 30% more than conical nozzle. The practical significance is that it is possible to obtain comparatively fair mixing in between l/d of 3-4 without having much stagnation pressure loss. So this can be considered as an optimum length for mixing of clover nozzle. In case of petal nozzle [5], the l/d ranges from 2.5-2.8.But the pressure loss is about 50% more than conical nozzle. Therefore it can be concluded that even though petal nozzle promotes mixing quickly, clover nozzle attains same mixing conditions without heavily compromising on stagnation pressure losses. These results are obtained as per above experiment conditions. A study in thermal mixing is also necessary to validate these results for further practical implementations.

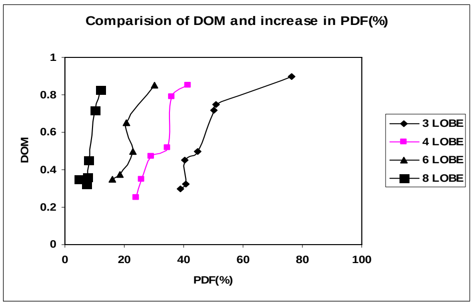

Figure 13

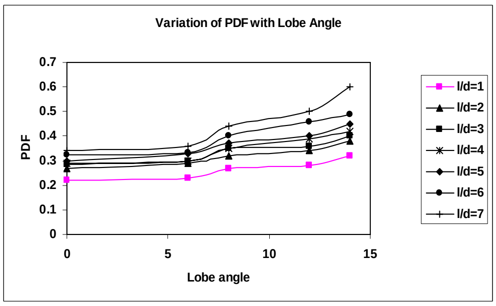

Figure 14

But the striking factor is that even though the six lobe shows better mixing, the three lobe clover nozzle possesses higher pressure loss. This can be seen in the Figure 13. The Figure 14 shows variation of PDF with lobe angle. The reason for higher stagnation pressure loss in the three lobe is due to the excessive angular deviation or redirection of flowing streams. This facilitates spreading of jet streams rather than enhancing mixing of streams resulting in considerable decrease in thrust. This indicates as lobe angle is increased, the flow redirection will be more producing high stagnation pressure loss. Following this trend, we can expect a two lobe cover nozzle will have more pressure loss than all these nozzles.

4. Conclusions

Among different nozzles tested, six lobed clover nozzle attained mixing within a short span at l/d=5.The mixing plane is neither the major plane nor the minor plane, but in between both planes. This reveals that vortices which cause mixing are generated in that plane.The mixing performance not only depends on lobe angle, the number of vortex generating planes also play a major role.As lobe angle increases, the vortex generating planes decreases for same exit area and vice versa.The nozzles shows an optimum performance when both lobe angle and vortex generation is balanced,hence six lobe showed complete mixing within short span. The flow redirection by lobe angle facilitates vortex generation but excessive lobe angle will result in pressure loss due to jet spreading rather than better mixing. When compared to petal nozzle, clover nozzles have less pressure loss for a given l/d but at the same time achieves good mixing without considerable decrease in thrust.

To have a thorough understanding about the physics of mixing, study of flow structure, shock formation, structure of vortices are to be analyzed. The present study is related to isothermal mixing. Thermal mixing behavior of clover nozzles is to be done to understand the temperature distribution pattern of supersonic mixing stream.

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