Numerical and Experimental Investigation Of Mixing Enhancement Using A Stepped Cavity With A Three Lobbed Clover Nozzle

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Abstract

Proper mixing between two high speed coaxial streams in a short mixing chamber is a necessity in hypersonic air breathing engines. To enhance mixing active and passive methods of mixing are employed together. The present study investigates a three lobbed clover nozzle with stepped cavity. Numerical investigations were carried out by varying the step ratio of the axisymmetric cavity. The mixing effectiveness of various configurations were analysed with the help of mixing parameters. The results indicate uniformity of mixing is better with clover nozzle with stepped cavity of step ratio 0.33. The experimental validation of the numerical analysis has been done.

1. Introduction

In hypersonic air breathing engines, the short residence time of air in supersonic combustor, the efficient mixing between coaxial flows is a challenge. Hypersonic propulsion devices like Air Augmented Rocket (AAR) and Dual Combustor Ramjet (DCR) having advantages of high impulse and high. altitude flight proper mixing of supersonic coaxial flows plays an important role in efficiency. In an AAR configuration as in figure 1 the combustion products fuel rich mixture at supersonic speed, enters secondary combustor mixes with the atmospheric air induced through converging air intake.

In a Dual Combustor Ramjet (DCR) as in fig 2, the air enters through a ramjet inlet and helps to burn fuel rich exhaust from primary in a secondary chamber. The mixing of supersonic flow in short residence time, the rate and uniformity of mixing has a major influence in the efficiency of combustion, heat release, size of combustion chamber and many other critical parameters.

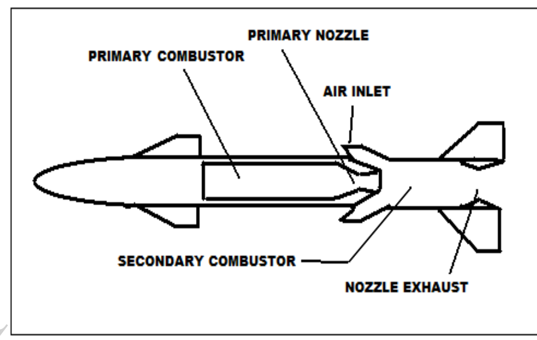

Figure 1 Air Augmented Vehicle

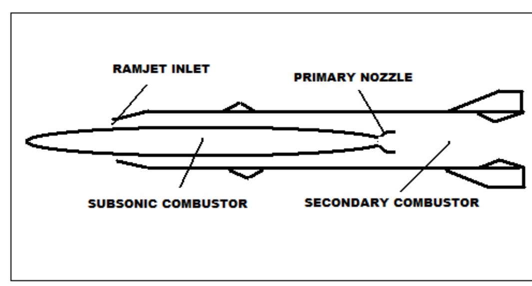

Figure 2 Dual Combustor Ramjet

Experimental studies showed that high speed jets shear mixing is retarded due to slow growth rate of shear layers as a result of compressibility [1]. Vorticity dynamics have a strong influence in mixing process. The stream wise vortices generated in a flow, in addition to the span wise (planar shear layer) or ring type (in axisymmetric shear layers) vortex rollup processes, have been found to mix fluid streams quickly and efficiently.

Mixing enhancement is brought by the introduction of active and passive methods. Active methods include inducing turbulence, shock, swirls by components like cavities, struts ramps etc. The passive methods include changing initial condition of the jet by changing geometry.

S.Jeyakumar and Balachandran.P [2] conducted an experimental study on mixing enhancement in supersonic streams with axisymmetric cavities. It is observed that wall mounted cavities enhance momentum mixing of two supersonic streams within a mixing tube at the cost of marginal stagnation pressure drop. Ben-Yakar and Hanson [3] investigated a high speed, high temperature flow over cavities to understand the fluid dynamics and flame holding characteristics. The shock wave structure around the cavity changes from compressive to expansive in nature as the ratio of length to depth of cavity increases from *l/d* = 3 to 7. For large values of *l/d*, the leading edge shock pattern gets diminished. Deepu et al [4] numerically studied that shock included vortex generation enhance mixing and reaction. They concluded that the shock reflections are responsible for blocking the development of jets and thereby creating the low velocity region. This increases the residence time of flow and hence increases mixing and reaction.

Three lobbed clover nozzle is introduced to add passive mixing. Studies [5] proved that a clover nozzle, radially lobbed nozzle provides better pressure recovery compared to lobbed nozzle. The clover nozzle can enhance mixing at high speed jet at marginal stagnation pressure loss compared to circular. The effectiveness is also been experimentally proved [6, 7].

Samitha et al. [8] experimentally and numerically studied the mixing performance of three lobbed clover with cavity configuration. Rectangular cavities with different *l/d* ratio, *l/d* =1 and *l/d* =1.66 are compared with conical nozzle with cavity in coaxial supersonic streams. Clover nozzle with *L/D*=4 and *l/d*=1.66 gave flat momentum flux distribution in the radial direction at the end of the mixing tubes.

From the literature, the mixing tube with *L/D*=4 and *l/d*= 1.66 is chosen for the work as it gives better performance with *DOM* and *PDF* in earlier comparisons.

In this study the effect of stepped cavity along with clover nozzle and circular nozzle in coaxial supersonic stream is analyzed by varying the step ratio of the stepped cavity.

The numerical results obtained are all experimentally validated.

2. Computational Methodology

Numerical analysis has been done using commercial CFD software ANSYS FLUENT. 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 3.

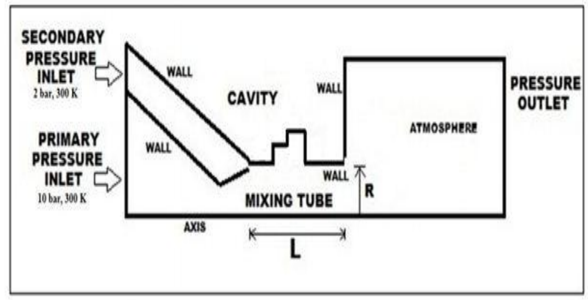

Figure 3 Schematic of circular nozzle configuration

For circular nozzle, an axisymmetric model was used with structured grid system having quadrilateral cells as shown in fig 4. For Clover nozzle, the grid system consists of hexahedral cells as shown in fig 5. For primary nozzle, the pressure inlet boundary condition is 10bar, 300K imposed at primary inlet. For secondary nozzle, pressure inlet condition 2bar pressure and 300K is implied. Pressure outlet condition with atmospheric properties (1.01325bar and 300K) set at outlet. Analysis is done with k-ω turbulence model with coupled implicit solver. The literature cast that the 3 lobbed clover nozzle with an axisymmetric cavity of *l/d* = 1.66 has an optimized performance considering the *DOM* and *PDF*

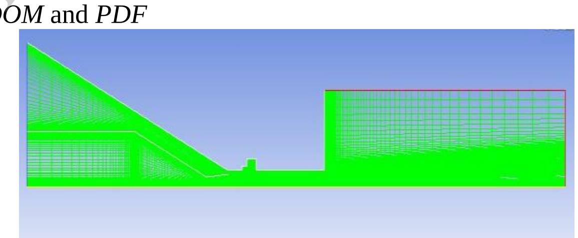

Figure 4 Grid system for cnical configuration

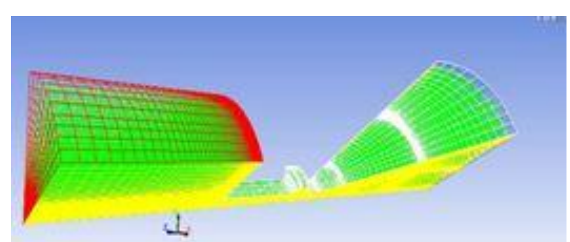

Figure 5 Grid system for clover configuration

3. Grid Independence Study

A grid sensitivity study has been conducted to arrive at an optimum grid for two dimensional and three dimensional numerical simulations. The grid independence study has been carried out in configuration with mixing tube L/D=4, axisymmetric cavity l/d= 1.66 table1. The results are found to be insensitive beyond 75470 cell for two dimensional conical nozzle and 172428 for the three dimensional clover cases.

TABLE 1 Grid independence test

Nozzle type	Number of cells	*DOM*
Clover Nozzle	163230	0.8300
	172428	0.8150
	177464	0.8120
	196400	0.8115
Conical nozzle	53954	0.5632
	68610	0.5520
	75470	0.5468
	79080	0.5421

4. Governing Equations

Continuity equation

$$\nabla.(\rho U) = 0$$

Momentum Equation

$$\nabla.(\rho UU) + \nabla p = \nabla.\tau$$

Energy Equation

$$\nabla.(\rho Ue) = -\nabla.q + \nabla.(U\tau) - \nabla(pU)$$

where *e* is the total energy

the viscous stress , $\tau_{ij} = 2\mu S_{ij}*$

the viscous strain rate , $S_{ij}* = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{1}{3}\frac{\partial u_k}{\partial x_k}\delta_{ij}$

the heat flux , $q_j = -k\frac{\partial T}{\partial x_j}$,

Turbulence Transport Equations

a. Kinematic eddy viscosity

$$\nu_T = \frac{k}{\omega}$$

b. Turbulence Kinetic Energy

$$\nabla.(\rho kU) = \nabla.[(\mu + \frac{\sigma * \mu_T}{k})\nabla k] + \tau\nabla U - \beta * k\omega$$

c. Specific Dissipation Rate

$$\nabla.(\rho\omega U) = \nabla.[(\mu + \frac{\sigma\mu_T}{k})\nabla\omega] + \frac{\alpha\omega}{k}\tau\nabla U - \beta\omega^2$$

d. Closure coefficients

$$\alpha = \frac{5}{9} \quad \beta = \frac{3}{40} \quad \beta* = \frac{9}{100} \quad \sigma = \frac{1}{2} \quad \sigma* = \frac{1}{2}$$

In addition to above equations, other relations are also used based on assumptions to simplify the problem.

a. State equation for ideal gas.

b. Calorically perfect gas- constant specific heat.

c. Flow field is assumed to be steady, effect of gravity is neglected.

d. Sutherland law for variation of viscosity with temperature.

5. Definitions of Mixing Parameters

5.1. Momentum flux (μ)

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

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

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.

5.2. 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

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

where σ_μ (x) is the standard deviation of the radial distribution of momentum flux at a given axial location in the mixing tube, μ_{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. The uniformity factor is used to define a mixing parameter called Degree of Mixing (*DOM*).

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 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 the mixing tube inlet stagnation pressure.

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

where, $P_{OI} = \frac{(P_{OP} \times A_P + P_{OS} \times A_S)}{(A_P + A_S)}$

Where P_{OI} and P_{OE} are the weighted average of total pressure at the supersonic combustor inlet and exit.

6. Experimental Setup

An experimental validation was done to the numerical analysis. The experimental setup consists of 1) Air Supply system, 2) Pipe lines for transfer of air to test set up, 3) Test set up, 4) Pressure Probe Traversing Mechanism, 5) Digital Manometers, and 6) Pressure Probe.
Air supply system consist of a high pressure compressor of 40bar working pressure and 3 storage tanks capable of storing 3000*l* with 44bar pressure.

6.1. Test setup

The test setup comprises of primary nozzle and secondary inlet and the mixing tube. The primary nozzles both conventional circular as well as 3 lobbed clover nozzle were used. The secondary nozzle is having sonic exit velocity. The mixing tube is mild steel prepared with stepped cavity. Different configurations are tested. The schematic of the test setup is shown in figure 6.

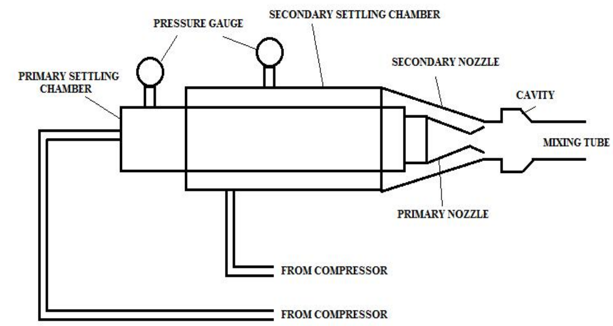

Figure 6 Schematic of test setup

6.2. Mixing tube

Mixing tube made of mild steel shaft with axisymmetric stepped cavities inside it is designed. The aspect ratio of mixing tube is fixed as 4 (*L/D*=4) and the cavity with *l/d*=1.66. For the measurement of static pressure a static tap is provided with a diameter of 1mm since according to the usual standards the static tap should have dimensions in between 0.25mm and 2.5mm. A static tap of diameter 1mm is provided on the surface nearer to the exit of mixing tube to measure the static pressure. The stepped cavity with step ratio 0.33 and cavity without step are casted.

Figure 7 The mixing tube

6.3. Pressure probe traversing mechanism

The pressure probe traversing mechanism is designed for measurement of stagnation pressure at various positions along the radial direction. The mechanism has 1000 mm Z movement and 200 mm

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movement length along X and Y directions. The probe used for stagnation pressure measurement is a hypodermic needle which is calibrated to standard probe. The probe is connected to digital manometer for readings.

6.4. Experimental procedure

The air is compressed and stored at 25bar in the storage system. Then the air is allowed to flow through the pipe lines by operating a regulating valve. The valve is opened up to a point when the stagnation chamber pressure of the primary stagnation chamber reaches 10 bar gauge and another valve is adjusted to get stagnation pressure of the secondary stagnation chamber reaches 2 bar gauge. The digital manometers are connected at the static port provided near the mixing tube exit and the pressure probe in the traversing mechanism. The static pressure and the stagnation pressure are thus measured. The experiment is done with conical and clover nozzle. The Clover nozzle is symmetrical about two planes viz major and minor planes. Hence measurements of stagnation pressure are taken along the two planes. The flow properties at the exit planes are measured, these properties can account for the mixing of the coaxial flows. The measurements taken are the stagnation and static pressure.

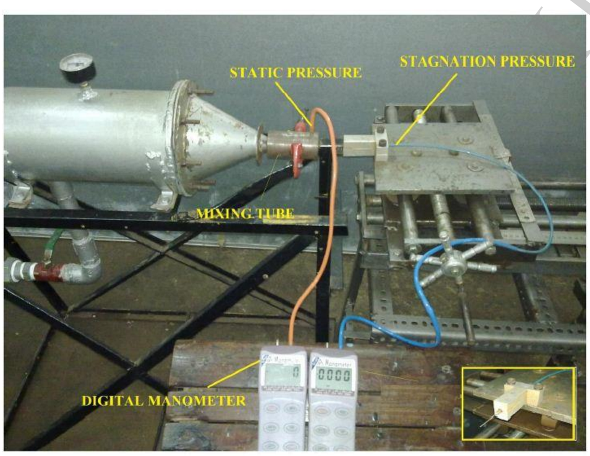

Figure 8 The experimental setup

8. Result and discussions

8.1. Momentum flux

The distribution of momentum flux in radial direction is a measure of bulk mixing. The figure 9 to 12 shows the radial distribution of momentum flux for various configurations of step ratios of axisymmetric cavities provided in the mixing tube. Results are presented for clover and circular nozzle with same mixing tube and cavity step configurations. Comparing with the conical clover has got much flat momentum flux in each case. The conical momentum flux is more flat for the case step ratio 0.25 and step ratio 0.33.

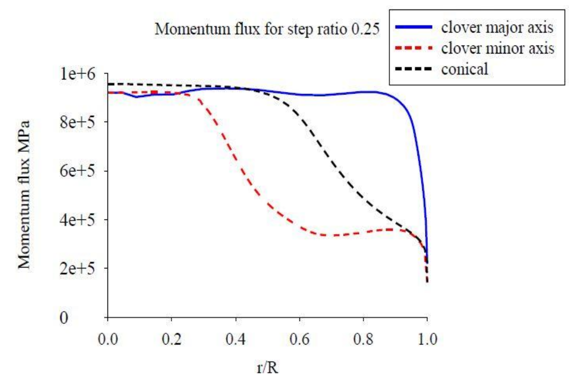

Figure 9 Radial distribution of momentum flux for axisymmetric stepped cavity with step ratio 0.25

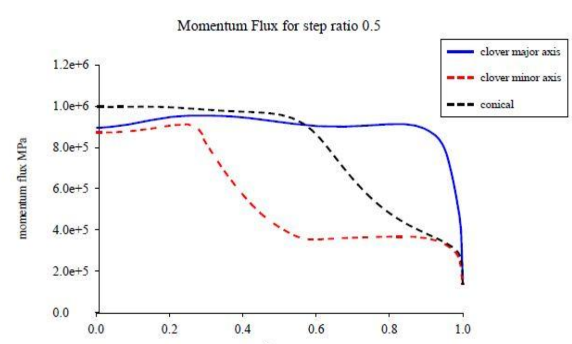

Figure 10 Radial distribution of momentum flux for axisymmetric stepped cavity with step ratio 0.5

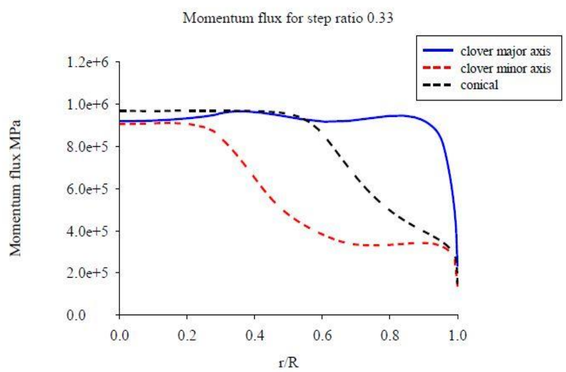

Figure 11 Radial momentum distribution of momentum flux for stepped cavity with step ratio 0.33

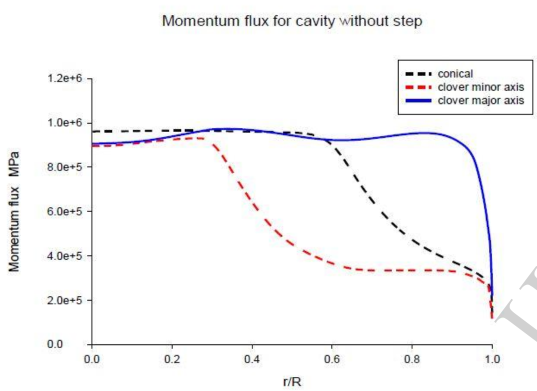

Figure 12 Radial distribution of momentum flux for axisymmetric cavity without step

In the case of clover, the major plane radial distribution of momentum flux are having same trend for all cases under study , if the minor plane momentum flux is closely observed , the case with step ratio 0.33 has a more flat and linear distribution of momentum flux (μ).

8.2. Degree of mixing

Results clearly indicate there is only slight variation in degree of mixing with the introduction of stepped cavity. The percentage rise in DOM for the step 0.25 is 3.07% and for step ratio 0.33 is 2.4%. The figure 13 and 14 compares the variation of DOM for various step ratios of stepped cavity in conical nozzle and clover nozzle respectively. It is evident that clover nozzle with axisymmetric cavity of step ratio 0.33 gives the best performance of mixing when compared to other cases.

The improvement of mixing parameter occurs in the minor plane, this shows that the mixing is more uniform between the major and minor planes of the clover nozzle when configured with a stepped axisymmetric cavity of step ratio 0.33.

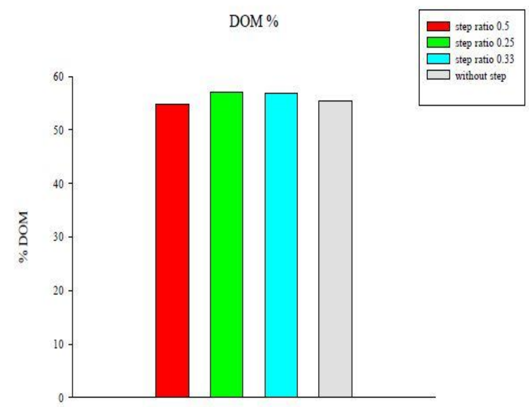

Figure 13 Comparison of DOM for different step ratio with conical nozzle configuration

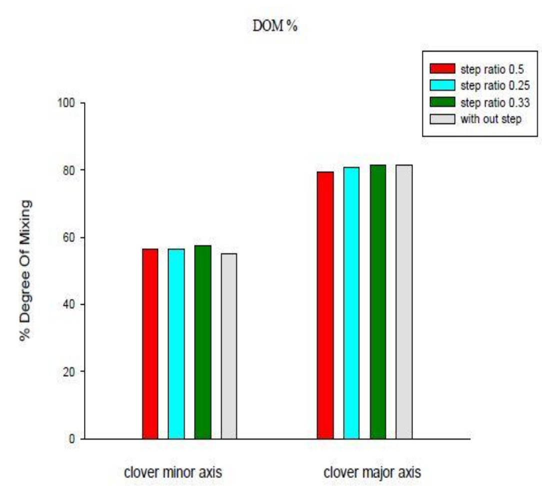

Figure 14 Comparison of DOM for different step ratio with clover nozzle

8.3. Pressure Drop Factor

The PDF comparison of conical cases as in fig 15 shows that the variation is very small, cavity with step ratio 0.33 holds with least pressure drop. Considering the PDF and percentage rise in DOM of 2.4%, step 0.33 may be considered the best optimum of cases under investigation in the class of a conical nozzle.

Figure 16 shows the comparison of PDF for various configurations based on step ratios of axisymmetric cavity along with clover nozzle. Considering the DOM values and comparing the PDF the case with step ratio 0.33 is to be selected an optimum as it attains a better improvement in Degree of mixing compromising slight increase in pressure drop factor. The additional pressure losses evident in clover nozzle may be due to complex shock patterns downstream of lobbed nozzle and the cavity. Stepped cavity accounts for an extra wall which could boost the shock thus pressure losses.

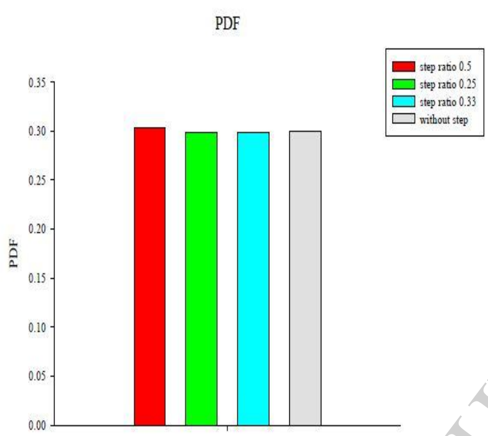

Figure 15 Comparison of PDF for conical nozzle with different step configurations

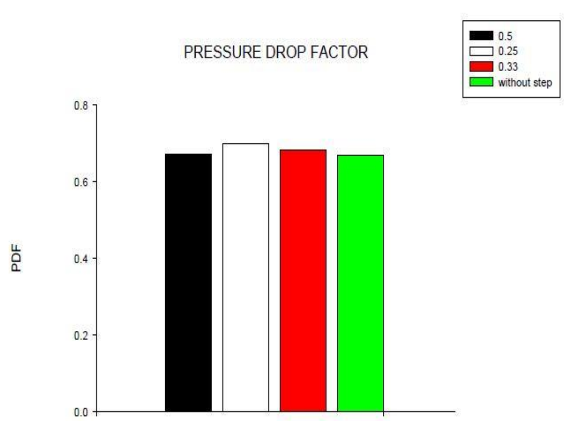

Figure 16 Comparison of PDF for clover nozzle with different step configurations

8.4. Experimental validation

The numerical results are validated by experiment. In figure 17 and 18 the momentum flux distribution of the numerical results are compared with experimental results. The graph depicts that there is small variation in the values of numerical study and experiment but shows the same trend. The deviation observed in the experimental results might be due to losses, assumptions in numerical analysis. The same trend shown by numerical and experimental results clearly indicates that the turbulence model selected is also much better to predict mixing analysis.

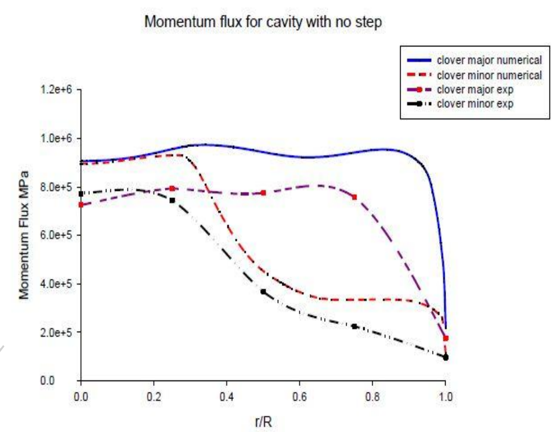

Figure 17 Comparison of momentum flux for cavity without step

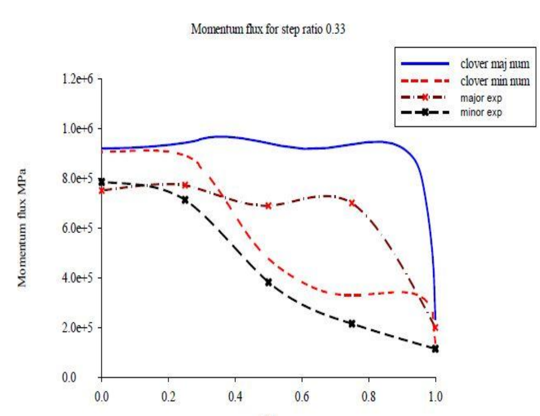

Figure 18 Comparison of momentum flux for cavity with step ratio 0.33

9. Conclusions

Numerical investigations conducted in cold flow to investigate the mixing performance of clover nozzle with axisymmetric stepped cavity with varying the step ratio optimised that a clover with stepped cavity of 0.33 step ratio outperforms the other configurations. The study is also conducted in conical nozzle with same set of step ratio. The conical case also shows the same trend, the optimum case for conical is axisymmetric cavity with step ratio 0.33.

The major conclusions drawn from the study are:

1) The 3 lobbed clover nozzle with an axisymmetric cavity *l/d* =1.66, stepped in the ratio 0.33 outperforms the other models. The configuration gives a flat momentum flux distribution in radial direction at the end of mixing tubes and more uniform between minor and major planes as the variation in degree of mixing between these planes is minimal in this case.
2) The value of Degree of mixing obtained for 0.33step ratio is 0.8146 and 0.5738 at major and minor planes respectively. Earlier it was 0.8150 and 0.5498 respectively with axisymmetric cavity without step.
3) In the case of clover the pressure drop associated with the 0.33 stepped cavity is more compared to the cavity without step, the sacrifice of pressure brings more uniform distribution of mixing and better *DOM* at the minor planes.
4) The percentage increase in *DOM* in the minor axis is 4.36% with the compromise of *PDF* 3.02% rise for the clover case.
5) For conical nozzle step ratio 0.33 is the optimum. In conical nozzle a rise of 2.4% for the *DOM* is obtained without much deviation in *PDF* from one without cavity.

The experimental results also proved slight improvement at the cost of stagnation pressure in the mixing tube. The enhancement in mixing obtained is not much satisfactory as we compare improvement by adopting active methods to supersonic streams. A stepped cavity does not bring much improvement in the effectiveness as expected.

10. References

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