CHAPTER I
INTRODUCTION

1.1 GENERAL BACKGROUND

The realization of efficient supersonic combustion is dependent on the mixing rate of the fuel and air streams. Mixing is an important phenomenon in all combustion systems from low speed systems such as coal fired – boilers, oil and gas fired furnaces and gas turbine engines to high speed systems such as air augmented rockets, dual combustion rockets, supersonic ejectors and scramjets. The term air augmented denotes the mixing of air with the rocket exhaust in proportion that enables the propulsion device to retain the characteristics typifying a rocket.

One of the major problems associated with the practical implementation of advanced aerospace propulsion concepts is the difficulty in achieving proper mixing between two high speed streams in a short mixing chamber. In air breathing engines the atmospheric oxygen will mix with fuel to propel the vehicle at $M > 7$. This requires a secondary combustion chamber in which the hot fuel rich gases from the primary rocket nozzle get mixed and burned with oxygen in the air supplied by the air intake system.
The rate and the uniformity at which a fuel and oxidant can be mixed have major influence on the efficiency of combustion, heat release rate, size of combustion chamber and many other critical parameters. Experimental studies showed that in high speed jets, shear mixing is retarded due to slow growth rate of shear layer as a result of compressibility. Here comes the importance of vortices. Vorticity dynamics have a strong influence in the mixing process. The stream wise vortices generated in a flow, in addition to the spanwise (in planar shear layers) or ring type (in axi-symmetric shear layers) vortex rollup process, have been found to mix fluid streams quickly and efficiently. The circular nozzle jet mixing process is well understood and is dominated by momentum transfer through the action viscous shear stresses and small scale turbulence in the mixing layer.

Some of the earlier attempts to enhance the jet mixing process involved the use of nozzles of different shapes like triangular, rectangular or square nozzles which showed that the introduction of sharp corners can significantly increase the small scale turbulence generated by axial vortices relative to flat segments of the nozzles. Recently, lobed nozzles such as petal nozzles also had undergone extensive studies. But the presence of sharp edges in petal nozzle generated shock waves resulting decrease in stagnation pressure with increase of entropy.

Studies showed that lobed nozzles are more effective in promoting mixing for the same length of mixing duct. The reason is lobed nozzles produce stream wise vortices more effectively than conventional methods, which aid the mixing process by entraining additional fluid from the secondary stream, in to the mixing layer and conversely sweeping in to the secondary stream. Thus lobed nozzle is an effective device for mixing two co-flowing streams of velocities and
temperatures. Lobed nozzle has a convoluted trailing edge, which alternately turns upper and lower streams in to lobe troughs. Because of these convolutions and increased interfacial area, strong stream wise vortices are shed at the trailing edge resulting in periodic stream wise vortices in the downstream mixing field. The stream wise vortices develop in to an array of counter rotating large scale vortices, which are believed to be primarily responsible for the enhancement of mixing process. This improved entrainment reduces the velocity of high speed exhaust gases, there by reducing noise. The stream wise vortices are set up by both primary and secondary flow but the contribution to the overall mixing process is still not clear. It is expected that the secondary flow vortices are playing dominant role in mixing.

1.1.1 Importance of Thermal Mixing

In the case of supersonic combustor application, the level of thermal energy content and its distribution are very important. The temperature distribution should be uniform and the resulting distribution be able to sustain combustion process. By thermal mixing it is possible to study the thermal energy distribution, as stagnation temperature is the measure of total thermal energy content. This is because uniformity in the stagnation temperature of jet is used to express the level of mixing. In the case of isothermal mixing only the momentum exchange can be measured. Another important aspect is the study of jet acoustics. This is because exhaust jet that mixes with ambient air from jet engine is hot which can be simulated only by thermal mixing. All these facts show that for propulsion application thermal mixing analysis is very important.
1.1.2 Need for Supersonic Combustion

In the case of ramjet engine, air admitted from ambient condition is decelerated to nearly zero velocity and supplied to combustion chamber so that flame stability can be achieved. But when flight Mach number reaches hypersonic speeds, the temperature resulting due to deceleration will be high enough to cause following problems:

1) High temperature will cause engine structure to fail by creep or fatigue.

2) At high temperature, fuel will dissociate as its dissociation limit is reached. Even if best available material to withstand thermal stress is provided, dissociation cannot be avoided. Because of this dissociation, fuel will absorb heat and ionize rather than undergoing oxidation. Thereby fuel may not be able to raise the thermal energy by undergoing combustion. So thrust developed by propulsive device drops drastically. The above problem can be solved by allowing air to continue at low static temperature which prevents medium from reaching stagnation temperature by keeping its kinetic energy high at supersonic speeds. Thus in order to operate air breathing propulsion at hypersonic flights, supersonic combustion is preferred. In supersonic combustion, problem of cooling combustor wall cannot be avoided as this depends on stagnation temperature. This problem is avoided by cooling walls using fuel on its way from fuel tank, thus fuel acts as sink. In this point of view hydrogen has got some advantage over other fuels because of its high specific heat.
1.1.3 Problems with Supersonic Combustion

Following are some of the problems faced by researchers regarding supersonic combustion.

1) Low residence time.

In supersonic combustion, flow speed will be about 1.5Km/s. If combustor is of 1m length the residence time of flow will be of the order of few milliseconds. This value is much less than the chemical reaction time for most of the fuels including hydrogen. So achieving stable chemical reaction and holding flame to sustain combustion are not possible directly.

2) Mixing problem.

As a result of low residence time, mixing of fuel into supersonic air stream is difficult. Also the growth of shear layer that favors mixing is slow due to enhanced compressibility at supersonic speeds. These facts make mixing of jet very difficult. Therefore any aggressive strategy to enhance mixing will cause large stagnation pressure loss due to shock wave formation at injector face.

3) Thermodynamic limitation.

Addition of heat in supersonic jet causes flow to decelerate and results in thermal chocking. Once thermal chocking is achieved, addition of heat is possible only by flow readjustment which depends on flow inlet condition. In the case of supersonic flow, addition of heat after thermal chocking will cause shock waves to stand at combustor inlet. These shock waves
not only cause stagnation pressure loss in combustor but also interact with inlet boundary layer causing it to separate and disrupt the velocity distribution and there by affecting combustion. This problem suggests the need for an isolator in practical supersonic combustors.

4) **Flame stability.**

Holding flame at supersonic speed is like holding a lighted candle in hurricane. Flame can be stably maintained in the regions of combustor where residence time is relatively large. Introduction of flame holders (like rods, perforated plates, and V shaped gutters) in main stream which is at supersonic speeds can cause stagnation pressure loss and disrupt the flow pattern. So cavity based flame holders are generally used to enhance mixing and flame stability. Shallow cavities are used for flame holding and deep cavities are used for mixing. Exact geometry of cavity is decided such that it should not cause vortex shedding and high stagnation pressure loss. In cavities, a circulation is formed which helps to re-circulate the flow there by keeping residence time higher.

5) **Proper source of ignition.**

One of the major problems in supersonic combustion is the need for constant source of ignition to sustain combustion. This problem can be easily avoided in the case of DCR or AAR, as thermal energy from supersonic primary jet is used to crack, vaporize the liquid fuel used. DCR or AAR configurations help to use hydrocarbon fuel like kerosene for supersonic combustor applications.
1.1.4 Thermodynamics aspect of Supersonic Combustion.

By theory of Rayleigh flow addition of heat in supersonic flow through constant area makes the following effects:

1) Stagnation temperature increases.
2) Static temperature increases.
3) Mach number decreases.
4) Static pressure increases.
5) Stagnation pressure decreases.

One of the major problems is thermal chocking of flow. It is possible to delay thermal chocking by providing diverging combustor walls. This also helps to reduce the slope of Rayleigh line in P-V diagram and helps to delay thermal chocking. This in turn increases size of combustor needed and hence its weight. Addition of excessive heat after thermal chocking can cause shock wave to stand outside the combustor in the case of scramjet.

Another important aspect is large increase in static pressure during supersonic combustion. This will have two effects on combustors.

1. Stress on combustor wall increases, which demands thick walls so weight of combustor increases.
2. Increasing pressure can increase adverse pressure gradient in boundary layer flow inside combustor causing it to separate as shown in Fig.1.1, which was one of the results of numerical analysis.
Another problem in supersonic combustion is that, addition of heat will cause stagnation pressure to decrease even if flow is supersonic or subsonic. This is according to relation,

\[
\frac{dP_0}{P_0} = -\frac{\gamma}{2} M^2 \frac{dT_0}{T_0}
\]

The above relation also suggests that stagnation pressure loss can be reduced by decreasing Mach number of supersonic stream during combustion. Because of this, supersonic combustion is usually attempted at Mach number range of 1.5 to 2.

Fig.1.1 Mach number plot in a scramjet model.

1.2 MOTIVATION FOR THE PRESENT STUDY

Several issues pertaining to the mixing and combustion inside a supersonic combustor still remain unanswered in order to realize the full potential of
propulsion system. The lobed nozzle has been identified as an effective device in mixing enhancement, only limited information is available on its use in a supersonic combustor. The application of lobed nozzles in supersonic combustors is a challenging area for research and detailed studies on this method can give valuable information for scramjet development. Results of the initial efforts on the use of lobed nozzle for supersonic combustion encourage further studies in this direction. By changing the shape of the petal nozzle (sharp edged nozzle) to wavy-nozzle (clover nozzle) studies were done expecting better mixing performance. Some changes in the shape of the mixing chamber were also done along with the shape of nozzle. This work offers a vast area for basic as well as applied research.

1.3 OBJECTIVE OF THE WORK

- The present work includes design and fabrication of three, four, six and eight leaf clover nozzles.

- Design and fabrication of a test facility and connected instrumentation by which the performance of the nozzle can be experimentally studied.

- Study the effect of lobe angle of clover nozzle on the mixing performance of clover nozzles on coaxial streams by conducting experiments.

- Computational analysis of supersonic mixing using clover nozzle.

- Validation of experimental results.

- Analyse the effect of axisymmetric cavities in coaxial supersonic streams and to compare the results with conventional nozzle.
• Carry out numerical analysis of supersonic combustion, test and compare the abilities of clover nozzle and conical nozzle by using Hydrogen as fuel.

1.4 SCOPE AND OUTLINE OF THE PRESENT STUDY

As indicated earlier the present work is an experimental study on mixing in supersonic flows. The study addresses the problem of mixing enhancement of coaxial supersonic jets using a three dimensional radially lobed nozzle, referred as clover nozzle. Due to experimental limitations combustion studies were limited to numerical studies. A brief outline of the work is given below.

1.4.1 Cold Flow Studies

In this part of the work the mixing of two coaxial jets both issuing at ambient temperature is investigated. A clover nozzle is used for enhancing the mixing. The mixing performance is compared with that of a conical nozzle. Stagnation pressure loss is also compared for the configurations. The effect of lobe angle of clover nozzle was also tested and the result shows that the mixing performance depends not only on lobe angle but also on the number of vortices generating planes for same exit area.

Here studies were done on active and passive methods of mixing enhancement for conical as well as clover nozzle and the results were compared. The effect of axi-symmetric cavities in coaxial supersonic streams were also analysed by varying the aspect ratio of mixing tube and cavities inside the mixing tube and with the help of momentum flux distribution analysis. As mentioned in the objective an experimental set up was established. Computational analysis of
supersonic mixing using clover nozzle was done and the results were validated with that of experimental results.

1.4.2. Hot Flow Studies

Simulated the thermal mixing aspect of three lobed clover nozzle and compared the results with that of a conical nozzle. Numerical simulation of supersonic combustion was also carried out for testing the ability of clover nozzle.