CHAPTER 1

INTRODUCTION

Ever since the Wright brothers have invented the piston engine airplane in 1903, tremendous amounts of time and effort were put into researching to build airplanes. Various types of airplanes were built to suit the civilian and the military applications. Design proposals of aircraft engines such as turbojet, turboprop, turbofan, ramjet and pulsejet have been around the world since the mid 1900s. The engines were invented to give better overall performance of the vehicle. The conventional turbojet, turboprop and turbofan engines are more suitable upto high subsonic speeds. Ramjet and pulsejet engines were being used as auxiliary devices to provide good performance in high subsonic to low supersonic speed range. It is well known that efficient operation of ramjets is limited to about Mach 5, which is equivalent to 5 times the speed of sound, beyond which efficiency decreases drastically (Curran 2001).

The desire for hypersonic flight necessitated the supersonic combustion ramjet (Scramjet) engine potentially expanding the speed envelope to the Mach 15 range. The term hypersonic refers to speeds in excess of Mach 5, i.e. 1520 m/s at a typical operational altitude of 32.5 km (Anderson 2007). It is efficient to decelerate the air entering the engines of aircrafts cruising at flight Mach number equal to 4 or 5 to subsonic velocity before entering the combustion chamber. For hypersonic flights such deceleration becomes more difficult and costlier in terms of total pressure losses and it is necessary to make provision for the combustion chamber to burn its fuel in the supersonic airstream. Prior to discussion on the details of the performance and design aspects of the supersonic combustion chamber, it is necessary to understand the working principles of ramjet engine and scramjet engine in which the combustion chambers are used. The following sections give an apt introduction of ramjet and scramjet engines. The Figures 1.1, 1.2 and 1.3 of this chapter can be obtained from the websites quoted in each figure. The author acknowledges the facilitators for creating such websites in the public domain with instructive and constructive information.

1.1 RAMJET ENGINE

Ramjet engine is the simplest of air-breathing engine consisting of an air-inlet, combustor and an exhaust nozzle (Hill and Peterson 1992). A schematic diagram of a ramjet engine is shown in Figure 1.1. In comparison with other conventional engines such as turbojet, turboprop etc, the ramjet engine does not have any moving parts (like compressor and turbine). During the operation the atmospheric air flows through these major components continuously. The function of air-inlet is to convert the kinetic energy of the incoming air into pressure energy called ram pressure. The high pressure air from the air-inlet flows into the combustion chamber where the fuel is injected and ignited for combustion thereby increasing the temperature of air fuel mixture to a high value. The products of combustion are allowed to expand in the exhaust nozzle and the resulting velocity is far greater than that of the air entering the engine. The increase in the momentum of air provides the necessary thrust in the direction of the flight. Ram pressure plays an increasingly important role in the thrust generation of the engine at the supersonic flight speeds. For flight speeds above Mach 2.5 or 3 the ram-pressure ratio becomes so high that a turbo compressor is no longer necessary for efficient thrust generation. Indeed, the pressure ratio eventually rises to such high values that the associated high ram temperatures make it difficult or impossible to place high-speed rotating machinery in the flow path without prohibitive amounts of cooling provision (Yahya 2003). This combination of circumstances gives rise to the ramjet, a jet engine in which the pressure increase is attributable only to the ram effect of the high flight speed; no turbo machinery is involved and the main thrust producer is an afterburner. Ramjets are lightweight and simple power plants making them ideal for the supersonic flight vehicles.

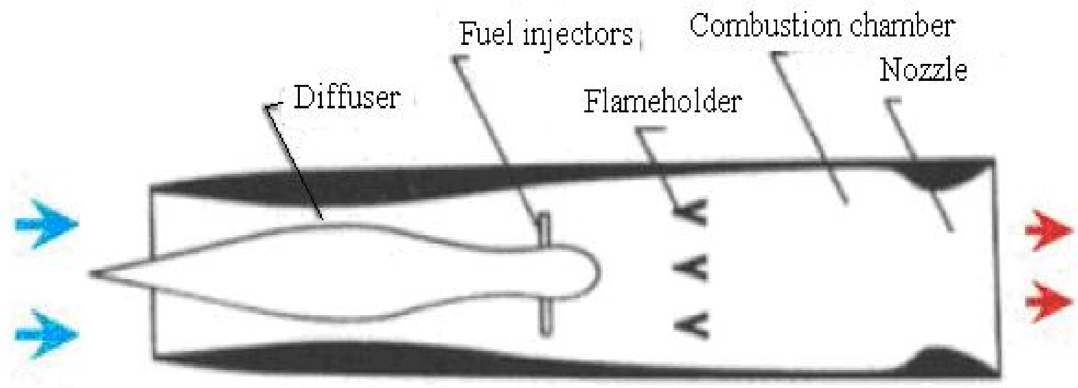

Figure 1.1 The schematic diagram of the ramjet engine (Source://www.aerospaceweb.org/question/propulsion/q0175.shtml)

1.2 SCRAMJET ENGINE

Ramjet engines are not suitable for hypersonic flights because the pressure and the temperature of the air entering the combustor increase as the cruise Mach number increases. When the flight attains Mach number values higher than 4, the temperature of the air entering the combustor is so high that it becomes difficult to add any more heat in the combustion chamber. The total pressure loss is also drastic across the normal shock making the operation of ramjet difficult at hypersonic flight Mach numbers. So, to propel the vehicles at hypersonic speeds, the air should still be moving at supersonic speeds when it enters the combustor (Hill and Peterson 1992). Thus, the combustion process itself takes place when the flow is supersonic. Hence, the name Supersonic Combustion Ram Jet (SCRAMJET) Engine. Figure 1.2 shows the schematic diagram of the scramjet engine.

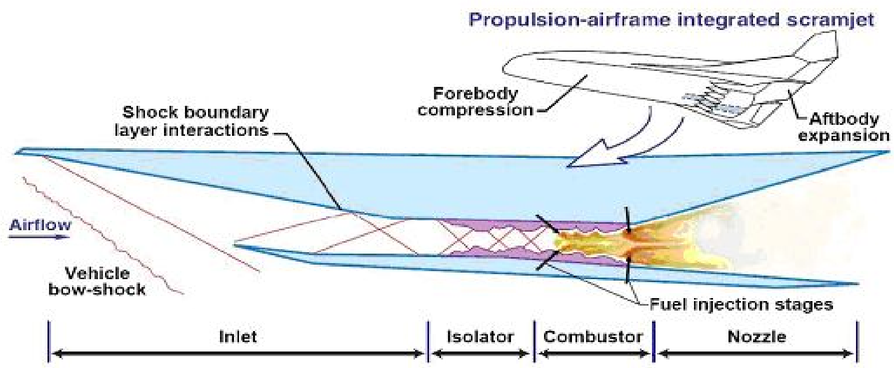

Figure 1.2 The schematic diagram of the scramjet engine used in hypersonic vehicles (Source: http://www.nasa.gov/centers /dryden/news/FactSheets/FS-040-DFRC.html)

In a Scramjet engine the air stream coming at hypersonic Mach numbers is compressed by a series of oblique shocks. The compressed air stream enters the combustor typically at Mach 2-2.5. The fuel is mixed with the supersonic air stream and burnt inside the combustor. The hot supersonic flow is allowed to expand in the nozzle thereby generating the thrust required for propelling the vehicle at hypersonic speeds. Intake design is very important as it is necessary to decelerate and compress the air with as little loss of total pressure as possible (Yahya 2003). Combustor design is also critical since the combustion must take place at supersonic speeds in such a way that enough heat is added to generate the required thrust. Too much heat addition will result in a normal shock standing at the combustor entrance. This is known as an inlet interaction. On the other hand, if too little heat is released the combustion cannot be sustained. The total residence time of the flow is of the order of 1-2 milliseconds. Within this short time the fuel should be mixed and burnt in the combustor and this requires highly efficient mixing strategies and effective flame stabilization methods (Gruber 1995). The increased combustor length needed for effective mixing will result in wall friction impulse losses, besides additional weight and structural cooling requirements (Guoskov 2001). So far National Aeronautics and Space Administration (NASA) is the only organization to have carried out successful flight testing of the scramjet engine. On 24th March 2004, an unpiloted X-43A (shown in Figure 1.3) aircraft with scramjet engine was test-fired by NASA. More flight tests are expected in the future to expand the data obtained in the previous test and put some scramjet vehicles in service (Andreadis 2004). In India, supersonic combustion wind tunnel tests are in progress at ISRO, DRDO and in IITs to evolve new strategies on supersonic combustion process. The Hypersonic Technology Demonstrator Vehicle (HSTDV) is the newly initiated project by DRDO to demonstrate the performance of the scramjet engine at an altitude of 15 to 20 km. The technology developed under `the HSTDV project will have multiple civilian applications. It can also be used for launching satellites at lower cost.

Figure 1.3 NASA's X-43A-Hypersonic scramjet powered research aircraft designed to fly at speeds upto Mach 10 (Source:http://www.nasa.gov/missions/research/f_scramjets.html)

1.3 THE FUEL INJECTION SCHEMES USED IN THE SUPERSONIC COMBUSTORS

As was mentioned in the previous section the overall performance of the scramjet engine depends on the efficiency of the mixing and combustion processes in the combustor. Several fuel injection schemes have been employed during the last four decades to enhance the penetration and mixing of the fuel injected into the supersonic airstream (Deepu 2007). The following is the list of fuel injection schemes found in the literature.

i. Normal injection of the fuel (Schetz et al 1968, Schetz 1970 and Rizzetta 1992)

ii Fuel injection with cavities (Rizzetta 1988, Davis and Browersox 1997 and Yakar and Hanson 2001)

iii Fuel injection through a ramp (Riggins 1990, Riggins 1992, Donohue and Mcdaniel 1996, and Aso 1997)

iv Co-axial or tangential/angled injection of the fuel (Bobskill 1991 and McCann and Browersox 1996).

v Single injection of the fuel behind a rearward facing step (Karagozian 1996 and Berman 1983)

vi Staged transverse injection of the fuel behind a rearward facing step(Abbitt 1992, Abbitt 1993 and Eklund 1994)

vii Fuel injection using aerodynamic ramp fuel injector (Eklund 1997)

viii Fuel injection with pylons (Owens 2001)

Different geometrical configurations and flow conditions have been developed to effectively disperse the fuel for efficient mixing and combustion, although usually there exist a tradeoff between rapid mixing and total pressure recovery (Hollo et al 1994). Each technique mentioned above has its merits and demerits. Attempts are being made by various investigators to combine two or more schemes to maximize the advantages and minimize the disadvantages. Also, the selection of the fuel injection scheme depends on the applications for supersonic combustion which are divided into four major categories (Billig 1993):

1. External burning devices for thrust production
2. Primary propulsion for missiles
3. Primary propulsion for hypersonic airplanes,
4. Thrust augmentation for fuel-rich rockets.

The key parameters of the mixing characteristics of any supersonic combustion chamber are (i) maximum mole fraction of fuel, (ii) penetration distance of the fuel, (iii) streamwise vorticity of the flow, (iv) percentage area of combustion and (v) average stagnation pressure of the flow (Papamoschou 1994). The goals of mixing augmentation are a higher reduction rate of the maximum mole fraction of the fuel, a higher penetration distance and a lower stagnation pressure loss. Higher reduction in the maximum mole fraction of the fuel results in enhancement of combustion process. Further, streamwise vorticity produces a large convection flow in the plane normal to the flow direction and promotes mixing. The higher percentage area of combustion implies better mixing ability of the combustion chamber. To avoid wall heating in combustor the penetration distance of the fuel should be high. An excessive loss of stagnation pressure should be avoided because it results in the loss of thrust.

In this thesis the focus is upon the detailed analysis of a staged transverse injection scheme which is employed in scramjet engines (Deepu 2006). Numerical experiments were conducted to find more efficient methods to augment the mixing characteristics of staged transverse injection behind the rearward facing step. It is predominantly a numerical investigation executed utilizing the commercial CFD code FLUENT.

1.4 ORGANIZATION OF THE THESIS

This thesis expresses the ideas generated after numerically researching the three dimensional flow through supersonic combustor models. Chapter 1 contains the introduction to the thesis. In Chapter 2 there is a review of the research efforts carried out by various investigators on the fuel injection schemes. The description of computational methodology adapted and the validation test conducted are given in Chapter 3. The flow conditions of models and the grid system used to perform the analyses after grid refinement study conducted are detailed in Chapter 4. The numerical results obtained for different combustor models with different flow conditions in this research are explained in Chapter 5. The findings of this research are summarized in chapter 6.