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Review Article

Scramjet Combustor Design - A Review

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ABSTRACT

Scramjet has been proven as one of the most promising propulsive systems in future gaining lots of attention of researchers and scientists. The complex fuel-air mixing phenomena inside the combustor are the major concern. This paper reviews about scramjet combustor design. It focuses on how the development of scramjet engine has taken place from scratch and the major challenges that has been faced. We have also focused on the major design considerations and fuel injection process that can lead to an effective design.

Keywords: Scramjet; Combustor; Design

INTRODUCTION

Supersonic combustor ramjet (Scramjet) is a descendent of Ramjets which utilizes atmospheric air for the combustion process and hence does not carry any fuel with it. It does not have any rotating parts like a compressor or turbine rather it relies on the forward speed of vehicle to compress the high speed free stream air (Mach>5) to supersonic speeds (ram effect), which increases the temperature and pressure of the incoming air. Since the free stream air is being decelerated, the flow properties of the air entering the burner is higher than in the free stream to a notably large extent. This results in making the engine incapable of slowing down the supersonic flow to subsonic speeds above Mach 5. This is the reason ramjets are find inefficient. In Scramjet engine, the flow is heated and slowed down to supersonic speed with lower Mach number in the inlet through series of oblique shock waves. This compressed air then enters into the combustion chamber where fuel is added to it for the combustion process to take place at temperature within the tolerable level and lastly a diverging nozzle accelerates the exhaust to hypersonic speed resulting in thrust. Expansion of flow in the nozzle serves two purposes- first, flow is accelerated to the external speed and second, a mechanism to convert increase in pressure into forward thrust is provided. We generally use a diverging nozzle for scramjet engine rather than constant area duct to avoid the limitations of heat addition due to thermal choking. A scramjet engine belongs to the Brayton cycle family just like other gas turbine engines, however due to absence of turbo machinery; the processes are little bit different.

Supersonic flow theory

We know the flow is said to be compressible only when it has variable density and Mach number more than 0.3. So in these types of flows, two important phenomena occur- Shock waves (when flow changes its direction in a convergent manner) and expansion waves (when flow diverges or expands). Across shock waves (both normal and oblique), we can observe drastic change in flow properties and these properties propagate throughout with the speed of sound. There is an increase in pressure, temperature and density while decrease in Mach number. However, we can see the opposite effects in case of an expansion wave where pressure, temperature and density decreases and Mach number increases.

LITERATURE REVIEW

The practicability of supersonic combustion ramjet started drawing attention of scientists and researchers by early 19th century. The possibility of adding heat directly to a supersonic stream, by means of a standing wave, was proposed in 1946 by Roy. At the first international congress in aeronautical sciences held in Madrid in 1958, Ferri briefly described some work and verified that steady combustion had been accomplished in a supersonic stream at Mach 3.0 without strong shocks. He was the leading figure in development of hydrogen fuelled Scramjet engines in these early years. Also in 1958, some work began at McGill University in Montreal reporting about inlets, fuel injection& combustion and exhaust nozzles focused on high speed range of Mach 10-25. Now we will see how scramjet technology developed in different nations.

USA

As mentioned above, Ferri emerged as a pioneer in developing hydrogen fuelled Scramjet engine with good performance over wide speed range in the United States. He proposed the idea of

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thermal compression where a three dimensional engine is coupled with wave compression effects produced by combustion which was theoretically possible at lower Mach numbers. The major drawback of this model was the difficulty in fuel injection to produce the desirable regions of thermal compression. He also examined hydrogen-air system and analyzed the problems of turbulent mixing, heat release and shock generation. After so much study and research, US air force was the first to fund two flight test engine programs IFTV and Low speed fixed geometry scramjet. Incremental Flight Test Vehicle (IFTV) was started by GASL (General Applied Science Laboratories) in April 1965. This test was planned to boost the test vehicle (four hydrogen powered scramjet modules were surrounding a central vehicle body) to 1645 m/s at an altitude of 17068 metres. Though a non-powered flight vehicle was launched in January 1967 but due to technical difficulties, the complete program was cancelled in 1967. The second one i.e., low speed fixed geometry Scramjet (aerodynamic contraction ratio differed with flight speed) was designed to operate without variable geometry within the range of Mach 3-12. This model made practical and effective use of Ferri's thermal compression approach, loosely integrated inlet combustor design, three dimensional aerodynamics and tailored fuel injection. Other than these two, US air force funded some more Scramjet engine programs like Marquardt dual mode engine, a general electric component integrated model and a united aircraft research laboratory variable geometry engine. Currently, they are working on a program HyTech which is aimed at developing a hydrocarbon fuelled scramjet engine. The two dimensional, dual mode engine with mixed compression inlet and fuel cooled structure has been developed by Pratt and Whitney.

Other than US air force, NASA has also put tremendous effort towards hypersonic scramjet technology. The very first was the Hypersonic Research Engine (HRE) with axisymmetric configuration which began in 1964. This program was focused towards flight testing of complete flight weight scramjet research engine on the X-15A-2 research airplane. However, the plan was terminated in 1968. Later on, two full scale HRE models SAM and AIM were developed for ground tests in 1970s. Structures Assembly Model (SAM) engine was a hydrogen cooled flight weight structure that was tested at Langley Research Centre in 8 foot high temperature tunnel at predetermined Mach. So many tests were conducted between 1971- 1972 to obtain the desired results. The second model AIM (Aero-thermodynamic Integrated Model) was water cooled, boilerplate engine design tested from September 1972- April 1974 for Mach 5-7 at John H Glenn research Centre. Total 52 tests were performed with an average running time of almost 2 hours which showed that the engine performance reached 70% of the standard performance and also exhibited the capacity of dual mode engine over a speed ranging between Mach 5-7. After HRE, scientists started focusing towards development of rectangular airframe integrated engine and a lot of work was done describing this concept by Henry& Anderson, Hearth& Preyss, and Northam& Anderson etc. The key features of this concept were the sidewalls of the inlet to provide horizontal compression in addition with the vertical fore body compression. Also, presence of in seam struts gives housing for various distributed fuel injectors. Both normal and parallel fuel injection to the stream is allowed and tailoring of the heat release is permitted in a diverging combustor. The configuration of modular scramjet engine with in seam strut fuel injection has emerged as the object of much research in recent years. Furthermore, an X-30 SSTO (Single Stage to Orbit) which was an experimental vehicle was developed under National Aerospace Plane (NASP) program in 1993 aimed at developing a hydrogen fuelled scramjet engine to function over a speed ranging from Mach 4 to Mach 15. But this program was closed due to shortage of funding in January 1995. X- 43A was an initiative of NASA to investigate the performance of an airframe integrated dual mode Scramjet powered vehicle. This is a 12 ft. long vehicle with 5 ft. wingspan launched with the help of a booster stage from B-52 aircraft. This vehicle attained the new speed record of Mach 7 and Mach 10 at an altitude of 12,000 metres during two flight tests that were conducted in the months of March and November in 2004 at NASA Dryden flight research centre respectively. After this, the National Aeronautics Space Administration is likely to focus on the large scale reusable Mach 6-7 vehicles and some undergoing programs like HyTECH, Hyper X Mach 15, Boeing X-51 and FASTT etc.

Russia

Scientists in Former Soviet Union (FSU) started showing interest in Supersonic Combustion technology during 1950s and so many research programs were carried out at various scientific institutions like CIAM (Centre Institute of Aviation Motors), TsAGI (The central Aerothermodynamics Institute), ITAM (Institute of Theoretical and Applied Machines) and MAI (Moscow Aviation Institute). Quite a number of research works were carried out primarily addressing the issue of mixing and combustion process that were being witnessed in 2D and 3D ducts with different fuels, flame stabilizers and fuel injectors with both scramjet as well as dual mode engine. An axisymmetric class and a fixed geometry 2D model was tested at CIAM with design Mach 6 using both hydrogen and hydrocarbon fuels. These engines came up with multiple cavity flame stabilizers and a three shock inlet. Two major vehicles Russia developed using supersonic combustion were HFL Kholod and IGLA. Kholod was a hypersonic flying laboratory with axisymmetric hydrogen fuelled engine and hydrogen cooling facility. Total four flight tests were performed from 1991- 1998 with French and American support to demonstrate that engine can be operated in both subsonic and supersonic combustion modes (dual mode). IGLA was a hypersonic flying test bed, a winged gliding vehicle accelerated upto Mach 16 with the help of booster RS-18. This was a three module, rectangular hydrogen fuelled engine with regenerative cooling.

France

The efforts started showing up by 1964 focusing on different fuel injection techniques (wall, strut and slot), use of both hydrogen and hydrocarbon fuels and divergent duct geometries. Some of the French programs were ESOPE (1966), PREPHA (1992), WRR, PROMETHEE and JAPHAR. All these vehicles demonstrated dual mode engine with hydrogen, hydrocarbon or kerosene fuels.

PREPHA was the first one designed by studying CFD<vehicle systems, materials and test facilities. WRR was a French- Russian program envisaged to attain higher speeds with the help of oblique detonation wave mode. Currently, French laboratories are working on JAPHAR (Joint Air-breathing Propulsion for hypersonic Application Research) which is focused to evaluate an H- fuelled dual mode engine which can operate up to Mach 22.

India

In India, an experimental mission towards Scramjet technology was been successfully conducted in 2016 at Satish Dhawan Space Centre in Sriharikota. The project was named as HSTDV (Hypersonic Technology Demonstrator Vehicle). The flight vehicle with hydrogen fuelled engine was test for a short duration of 6 seconds at a flight Mach number 6. With this India became the fourth nation to successfully demonstrate this technology keeping all the critical challenges in mind.

By late 19th century, many other nations like Germany, Australia etc., started embarking on supersonic combustion research through various programs. Also both analytical and experimental studies are reported by the Chinese Academy of Sciences, People's Republic of China.

Design considerations for airframe - Engine integration concept

The airflow entering the engine module inlet is compressed by the virtue of shock produced by the bow of the vehicle. The modular concept where several rectangular engine modules can be arranged side by side in the wide space available between the vehicle under-surface and the bow shock. Also, the vehicle after body can be used as an extension to the nozzle to allow higher effective exhaust velocities with comparatively modest area expansion in the modular nozzle and low engine external drag. However the major disadvantage of this design is the relatively thick turbulent boundary layer which is generated on the fore-body of the vehicle.

Technological challenges

The three major problematic areas in scramjet design are the air inlet, the combustor and structures and materials with combustor being the most formidable one. Some of the common problems related to these areas are the inlet starting issue, difficulty in ignition of fuel in supersonic mode, and ignition of fuel outside the combustion chamber because of the extra ordinary velocity. Now here are some of the paramount design challenges such as:

1. Mixing, ignition and heat release (all in supersonic flow) which involve complex supersonic and hypersonic flow theory. The mixing of the air- fuel mixture should be promoted in such a way, that within the really small residence time of the air-fuel mixture in the combustion chamber, chemical reaction and heat release occur.

2. Divergent processes for fuel injection.

3. Supersonic flow theory involved in mixing and combustion.

4. Elements behind the losses within the combustion chamber [1].

There is also a lack of steady flow test facilities for vehicles operating at Mach number 8 or above. Test facilities are essential in helping us understand the complexities in the flow involved in scramjet operations. Only free piston shock tunnels are available for test at higher Mach numbers with a time interval of few milliseconds. Also standard scramjet facilities operate in a blow down due to high power requirement for continuous operation. Then comes the mathematical modeling of combustor to simulate Reynolds number, boundary layer transition and component level testing in order to predict flight test performance on the basis of ground test results. The problems rise with developing an algorithm to solve N-S equations to capture sharp gradient zones around the shocks and the prediction of wall heat transfer. Some other challenges are the requirement of an extra propulsive system to drive the vehicle to the desired start velocity, need of some finesse for adequate performance over a large Mach number range with a practical engine. High pressure generated due to difference in stoichiometric heat of combustion and kinetic energy of the airflow is also a matter of concern [1].

Combustor design considerations

Among the scramjet's critical components, its combustor provides a lot of complex issues. Supersonic combustion is tricky. It involved turbulent mixing and shock interaction. The flow field is intricate and challenges the designers to design a combustor with a geometry that facilitates the combustion process. The combustor should allow optimal mixing of the air-fuel mixture so that the desired reaction can occur in the time the mixture is present in the combustor. According to Segal a constant area combustion chamber can lead to a very quick pressure raise which can lead the inlet to unstart because it is very difficult to control. According to Heiser and Pratt (1994) one can prevent this from happening and that is by using a divergent combustion chamber. This type of combustor makes sure the pressure does not rise or fall during the combustion process along the flow while also compensating for the heat release effect. Furthermore, it is suggested by Diskin and Mundi that the combination of a section with constant area followed by a section with a divergent flow path can lead to a better mixing and flame holding characteristics therefore improving the total efficiency. Heiser and Pratt suggest that a half angle between 3 and 5 degrees be set for the diverging part [2-5]

Heiser and Pratt also suggest that the mixing length of the combustor be 2.22 times the height of the combustor for optimal combustion. The length of the combustor is an important factor to consider because an appropriate length has to be enough to mix the fuel and air and then allow enough time for ignition and reaction of the air fuel mixture. The combustor length is the sum of the required lengths for mixing, ignition and reaction. And it is regarded as more cost efficient to have the combustor length to be as small as possible with as little skin friction drag as possible. Keeping the aforementioned in mind, a good design of the combustor aims to achieve the following [6-9].

1. Reduce total pressure loss as much as possible

2. Efficient and rapid mixing of the air- fuel mixture

3. Good efficiency of combustion

An engine integrated airframe is the most favorable concept for the scramjet design as it takes into account the fact that the decrease in take-off weight due to absence of an oxidizer must not be neutralized by extra engine mass required [5,8]. To accomplish this, a good and clear understanding of various fuel injection processes and processes governing supersonic combustion are required [5,8].

Fuel injection processes

Due to the milliseconds and microseconds of fluid residence within a scramjet reactor it is important to make sure that the mixing of fuel and air is as efficient as possible. Therefore, the design of the fuel injector and resulting length of mixing of the air-fuel mixture is an important aspect of a combustor Some traditional approaches are described below.

- Parallel, perpendicular and transverse-parallel injection involves fuel flowing parallel to the flow of air in the combustor but separated by a thin plate, known as a splitter plate. When the two separate flows reach the end of the plate, the different velocities of fuel and air flows create a shear layer. This layer is the main area of mixing the two flows in preparation of proper combustion. The flaw of this method is that it needs long distances for efficient mixing.

On the other hand, perpendicular injection involves an injector on a wall of a scramjet. As the name suggests, fuel is injected perpendicular to stream of air in the combustor. This type of system creates a detached normal shock upstream of the injector as well as downstream of the injector. The downstream separation regions have been found to work as flame holders. This type of injection has shorter mixing distances but larger momentum losses. Last but not least, there is transverse fuel injection, which is nothing but the combination of parallel and perpendicular fuel injection. The fuel is injected at an angle to the air flow. Compared to perpendicular injection, transverse injection requires greater injection pressure to achieve the same penetration height into the air flow [3].

- **Ramp injectors:** Ramps are placed along the combustor walls with injectors at the trailing edge of the ramps where fuel is injected parallel to the flow of air. The flow over ramps creates counter rotating vortices that increase mixing. The ramps also create shock and expansion fans resulting in pressure gradients. These pressure gradients also contribute to better mixing of fuel and air. Unfortunately, due to the fact that ramps are placed on combustor walls, the fuel penetration is limited and therefore a new method is required that promotes mixing between fuel and air throughout the flow in the combustor [3].
- **Strut injectors:** Covers an extensive range of designs which include both parallel and perpendicular injection techniques. Commonly, struts are vertical with a leading edge in the form of a wedge. Since the strut is fixed to the bottom and top walls of the combustor, fuel injection takes place at many locations and therefore fuel is mixed with air throughout the combustor [3].
- There are numerous other designs of fuel injectors such as Plasma ignitors, Pylon injection, Barbotage injection etc. These designs are more complex and intricate than the ones explained earlier and hence will not be looked at.

Flame holders

A flame holder is a component designed to help maintain continual combustion by creating eddies to prevent the combustion from petering out as well as to reduce ignition delay time [10-13]. The most common type of flame holder we have come across is the V-gutter type bluff body. Because the flow is supersonic, the high velocity flow is attached the surface of the body and a symmetric recirculation pattern is formed behind the bluff body where the air fuel mixture can mix more efficiently at slightly lower velocities.

Another common type is the wall cavity, which is a cavity on the wall in the middle of the flow of the air fuel mixture. This type of cavity offers little pressure loss and therefore sustained combustion. Furthermore, the drag associated with cavity type flame holders is significantly lower than that off bluff bodies. However, its disadvantages are that it creates losses in stagnation pressure as well as a reduction in total temperature. Mixing and combustion efficiency are greatly improved and the length of the cavity has to be such a length that it promotes a sustainable vortex to provide sufficient mixing inside the cavity.

CONCLUSION

This paper reviews about scramjet combustor design. It focuses on how the development of scramjet engine has taken place from scratch and the major challenges that has been faced. We have also focused on the major design considerations and fuel injection process that can lead to an effective design.

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