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Research Article

Overview of Dual-mode Operation of Scramjets

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Abstract

The scramjets are an emerging technology in the field of air-breathing propulsion. They not only ensure higher efficiency to produce thrust at the supersonic and hypersonic velocities, where only alternatives are the rocket engines, but also increase the safety and economy of the flight. The scramjets are specifically viewed as to potentially supervene the rocket engines in the atmospheric stage of the space launch. The associated phenomena with design of the engine are complex and require deep studies and experimentation, which have been explored by various researchers since the last half-century. This paper is aimed to provide an insight into the time-tested popular trends in the development of scramjets, their engineering considerations, experimentation and their modifications such as the operation in dual-modes to extend the operational range and the flight validation that has been carried out until now.

Keywords: *Air-breathing propulsion, Dual-mode scramjet, Hypersonics, Scramjets, Supersonic combustion*

1. Introduction

Half a century ago, during the 1960s, missile development technologies started to focus on laboratory experiments and demonstrations of supersonic combustion. These efforts were boosted in the 1970s and the 1980s when NASA Langley Research Centre started a research program to investigate the operational feasibility and performance characteristics of the airframe integrated scramjets to be flown at the speeds of Mach 7 and also to investigate their performance on ground testing, development of supersonic wind tunnels which can produce fairly identical flight conditions that these engines encounter during their operations.(R. Stalker *et al*, 2005) The evolution of aviation propulsion technology went from the propeller driven aircrafts of the early stages of development, followed by a large transition with the advent of Jet engines. The efficiency of combustion achieved by the Jet engines in their operation region in terms of I_{sp} (Specific impulse) is the highest compared to all other forms of air-breathing propulsion. The Jet engines utilize a compressor (Centrifugal or Axial) at their inlet which compresses the incoming air and increases its static pressure and temperatures. These temperature and pressure values are sufficient for the combustion of the fuel at the next stage of the engine, i.e. the combustor region, where there are usually 6 combustors placed axi-symmetrically around the central driving shaft connecting the turbine to the compressor. These engines, utilize a continuous combustion flow, not encountered in the previous reciprocating engines which have to run on a number of strokes for example the 4-stroke cycle. The continuous operation of the Jet engine ensures a constant thrust generated for the aircraft. Further the hot gases from the combustor are then expanded in a converging nozzle at the end of the engine to generate thrust from their relative velocities with the engine. The main characteristic of the jet engines is the subsonic speed of the flow throughout the engine.

Recent applications have displayed the optimization of these engines with military aircraft such as the Sukhoi Su-35 which can travel at supersonic speeds of Mach 2, but largely in airliners and in civil aviation, the operating speeds of travel are limited to the subsonic – transonic region. This can be a limitation for further increase in travel velocities for quicker requirements. As the inflow velocity of the air increases, the total energy contained in it also increases and hence the rise in static pressure and temperature made by the compressor becomes increasingly unnecessary. At speeds of up to Mach 3, the engines can still produce thrust without the compressor. As there is no requirement of the compressor, the turbine section downstream of the combustor is also removed. The remaining engine is termed as the 'ramjet' engine. This engine utilizes the 'ram effect' generated by the high velocity of the incoming air, mostly by means of shock wave formations at its inlet, which increase the total temperature and the static pressure of the air, but the velocity remaining essentially subsonic, making it suitable for combustion as soon as the fuel is injected in the combustor region. However, as the inflow

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velocity starts increasing above Mach 6, the intensity of the shock wave created at the entrance starts increasing and a large static pressure ratio and temperature ratio across the shock wave is obtained. This promotes the thermal choking of the engine downstream as the heat addition, according to the Quasi 1D analysis of the flow through the engine suggests that the flow velocity cannot increase beyond the Mach 1 value when it is initially subsonic, by heat addition. (Heiser and Pratt, 1994) Hence at higher Mach inflow values, to achieve the supersonic velocities through the combustor, the inlet needs to be modified. This is where the engine is categorized as the scramjet engine.

It utilizes the oblique shock waves generated at the inlet in a set of stages to modify the direction of flow, increase the static pressure and temperature of the flow prior to the combustor. Due to the absence of any heavy turbomachinery in these engines, the engines yield a higher power to weight ratio. The scramjet engines due to their structure are often integrated in to the airframe itself, being a part of the overall geometry of the airplane. The scramjets essentially have a converging inlet section, a constant cross-section combustor section and a diverging nozzle in accordance with the change in flow properties of the supersonic flow to increase the flow velocity at each stage. The operation range of the scramjet engines reigns at a flight altitude of about 25 km and with Mach number greater than 6. The upper limit of the operational capability of these engines is not clearly determined, but can be said of up to Mach 14, as beyond that, the drag associated with atmospheric travel increases tremendously and the thrust generated by the engine increasingly fails to accelerate the vehicle. All of the endeavours of mankind into the hypersonic speed region have been characteristically designs up till now to spend as low time as possible at those high speeds in the atmosphere, such as the rocket ascent and the atmospheric re-entry vehicles. In case of hypersonic flights, the vehicle and the engine technology both have to be capable of enduring and performing under prolonged hypersonic velocities.

2. Comparison of scramjets with other forms of propulsion

Scramjets, still being a form of air-breathing propulsion at hypersonic speeds, yield higher I_{sp} values than the rocket engines to which they are often compared.

Hence, the advent of scramjets is often viewed as a replacement for the atmospheric flight stage for rocket motors during space launch. Scramjets can be designed to increase the safety and economy associated with the space launch, a condition to be satisfied if private businesses are to step in to this field, only after which the full potential of space travel can be exploited. Rockets are increasingly reaching their limits in these criteria and thus switching to re-usable vehicles is seen as the only way forward. (R. Voland *et al*, 2006)

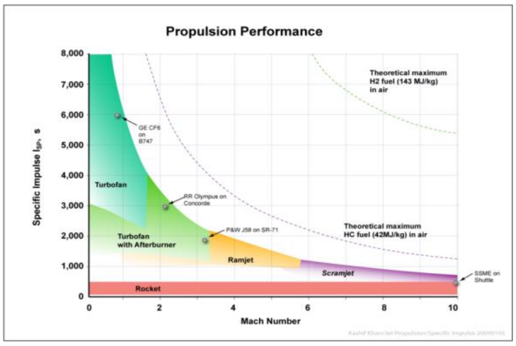

Fig. 2.1 Plot of Propulsion Performance showing Specific Impulse (I_{sp}) vs Mach Number regions of different forms of propulsion. (R. Voland *et al*, 2006)

3. Application of scramjets in flight-tests

NASA's New Generation Launch Technology (NGLT) has invested in the research of hypersonic air-breathing propulsion and vehicle technology with the same objectives of increasing the safety and economy of the space launch. The air-breathing propulsion systems can also facilitate a horizontal airplane-similar take-off for a space launch. (P. Moses *et al*, 2004) NGLT propulsion technologies comprise of the Dual-Mode Scramjet engines (DMSJ), Rocket Based Combined Cycle (RBCC), and Turbine Based Combined Cycle (TBCC). The primary objective of the NGLT flights, termed as the 'Hyper-X' program, is for experimental validation of the designs, design tools of the hypersonic propulsion, hence to achieve economic technology development goals, these propulsion technologies are tested with contemporary available vehicle technology, which might be at a lower Technology Ready-ness Level (TRL) of 6 as is the goal of the program. Nonetheless, the performance observations recorded from these flights can be used as a source of initial data for future research in this area. The overall objective of the NGLT is to have a building block type of approach in this research, structured decisive points throughout the research and off-ramp cost effective research and specific goals such as – reducing the flight weight, utilizing actively fuel-cooled structures, reusability and durability testing, scramjet operation over a larger Mach range including mode transition, combined cycle testing, powered operation over a larger test time, hypervelocity (greater than Mach 15), integrated vehicle health monitoring, expansion of operational models, validation of analytical method and design tools and development of cost-effective flight models.
The success of the wind tunnel testing carried out was also underlined in the validation of the designs in flight tests such as the 'Hyshot' launch conducted by the University of Queensland. The Hyper-X program initiated in the 1995-96 period was the first comprehensive flight test of the scramjet propulsion technology which was already developed owing to the extensive ground based research which was carried out on this subject since the mid-20th century.(R.

Stalker *et al*, 2005; McClinton *et al*, 2005) The initial success at Mach 7 of the airframe integrated scramjet engine was an essential step towards the demonstration of their capability towards their desired goal of being a worthy replacement in the space launch. (McClinton *et al*, 2005) Program goals included the collection of test data for performance prediction, reduce the development risks for further designs, flight validation of the airframe integrated design, and testing of new key technologies. This program exhibited a low-cost approach to design and build. The flight test models were dropped from the NASA's Dryden B-52 carrier aircraft at an altitude of about 30.48 km and the atmospheric pressure being 47.88 kPa. The flight test model was then accelerated to its operation Mach range of 7-10 with the help of a modified Pegasus rocket motor, which was separated once the model was self-accelerated. These were the minimum requirements from the airframe integrated model to be demonstrated regarding the approval of this research project in its initial stages. These successes answered to the main hurdle associated with their testing, of the cost effectiveness.(McClinton *et al*, 2005; P. Moses *et al*, 2004)

The transformational capacity of airframe integrated scramjets in air-breathing propulsion is often regarded as equivalent to the transformation bought about by the advent of Jet engines. (R. Voland *et al*, 2006)

4. Technical aspects of scramjet propulsion

In a scramjet engine, it is essential for the fuel-air mixture to remain at supersonic speeds throughout the combustor. If the heat addition in the combustor exceeds a particular value or the length of the combustor exceeds a particular value, the flow becomes thermally choked and there is a generation of a normal shock wave at the entrance of the engine which initially itself reduces the velocity of the flow prior to the combustor (R. Stalker *et al*, 2005; S. Byrne *et al*, 2000). This is known as 'unstarting' of the engine, resulting in heavy losses of energy. In the engine as the residence time of the fuel-air mixture is very less because of its high velocity, the phenomena of fuel injection, mixing and combustion become critical for operation. (S. Aso *et al*, 2005) Efficiency and quicker mixing, combustion and less overall stagnation pressure losses are required for the efficiency of the engine operation. Recent investigations into this have reported that the constant area combustor provide a higher static pressure rise in the supersonic combustion.(S. Byrne *et al*, 2000) The requirements of flame holding and efficient combustion methods instigated a study into the mixing and combustion phenomena. The transverse injection of the fuel into the cross-flow was most popularly investigated (S. Aso *et al*, 2005). The transverse injection generates a strong pre-combustion bow shock wave upstream of the injection point. This recirculation upstream of the injection point serves as the flame holding. The interaction of the shock-wave generated with the boundary layer causes the boundary layer to separate from the walls of the combustor. The region downstream up to which the boundary layer re-attaches also serves as flame holding. The total injection pressure of the fuel also has an important role in this as it determines the penetration of the fuel into the cross-flow and the intensity of the upstream bow-shock generated. The change in the profile of the combustor such as shift from a divergent cross-section to a constant cross-section downstream of the injection point induces an oblique shock wave in the flow. It has been experimentally proven that the generation of these shock waves proves to be an accelerator for the combustion process as the combustion starts just downstream of the oblique shock, making a case for combustion accelerators.

5. Dual-mode scramjet (DMSJ)

In the popular operation conditions of the scramjet engine, between 18-30km altitude and Mach range of 4-7, the dual mode scram mode fuelled by Hydrogen and hydrocarbon provides the most competitive form of air-breathing propulsion. (Q. Chen *et al*, 2013) The transition from the earlier discussed ram mode to scram mode is not as discrete as it might seem and occurs over a range of operation conditions. (Z. Yang *et al*, 2014) There have been investigations to study the effect of the fuel type, equivalence ratios, injector configuration, inflow stagnation temperatures and fuel injection distribution on the transition phase. In order to classify the operation modes of the engine, the definitions or the characteristics associated with the judgement of the modes must be established primordially.

6. Categorization of the modes of DMSJ

Definition first established by Heiser and Pratt, state that in order for the flow to be subsonic at the inlet, there must be generation of normal shock wave of sufficient intensity which implies that the flow needs to be thermally choked somewhere downstream, explaining it to be the ram mode. (Z. Yang *et al*, 2014) This is strongly correlated with the accuracy of Quasi 1D analysis of the engine, using Rayleigh and Fanno flow relations for the flow through combustor. Similarly, Rockwell used the condition of the subsonic speed at inlet as the deciding factor of the modes, the velocity being less than one, marks the ram mode.(Heiser and Pratt, 1994; Z. Yang *et al*, 2014) As the minimum velocity of the flow need not be at the inlet section, there is obvious possible differentiation between these two criteria. Aristides *et al* used the maximum pressure generated in the combustor as the criteria for definition of the mode. (Z. Yang *et al*, 2014) A pressure ratio of minimum 2.8 was necessary to thermally choke the flow, however but as they did not consider the ratio of the area of the combustor to that of the inlet, this may result in the over estimation of the transition point. Cabell *et al* used the fact of the sudden rise in the static pressure inside the combustor. If the pressure rise was not evident in the pre-combustor region, implying that there was no generation of a pre-combustion shock wave and the values of static pressure, total temperature and Mach number of the flow was similar to the inlet conditions upstream of the combustor, marking the scram mode of operation. In the ram mode, a strong pre-combustion shock is generated. However, their consideration of just 2 modes of operation might result in the underestimation of the transition point. Different from the above mentioned criteria, German and Japanese researchers used the categorization of weak and intensive combustion. The weak combustion, characteristically producing a weak plume and low thrust marked the scram operation and the intensive region, having larger (almost double) thrust and bright plume marking the ram mode of operation at the considered inlet Mach number. Quantitative analysis on the mode of transition is scarce, there only being one equation given by Heiser and Pratt for the inlet Mach number and the thermally chocked flow temperature, giving way to a relation of heat addition by the fuel, in terms of its equivalence ratio (ER). (Z. Yang *et al*, 2014)

7. Characteristics of DMSJ

As an essentially bi-stable system, DMSJ displays non-linear characteristics and hysteresis, which was evident from these experimental results – when the ER was increased to a value of 0.22 from lower values, there is no pre-combustion shockwave generation and the combustor entrance Mach number is 1.6, implying the engine running in scram mode. On the other hand, when it is decreased to 0.22 from higher values, there is generation of a pre-combustion shock wave and the combustor entrance Mach number drops to 1.2, meaning it to be operating in the dual-mode scram mode. Z Yang *et al* conducted an investigation on this and the main objectives of their study were to investigate 3 modes of combustion – dual mode ram mode, dual mode scram mode and the pure scram mode on the basis of changes in ER, 2 critical ER separating the three combustion modes.(Z. Yang *et al*, 2014)

Preliminary analysis of the combustion modes showed that the ER values have a significant impact on overall combustor flow properties, but only a moderate impact on the ignition position inside the combustor, before which there is a region of unreacting flow and mixing of the fuel-air components. The effects of these ER values attenuate as the free-stream velocities at the inlet of the engine increase. Comparative study was done between 2 different combustor geometries and various parameters were studied as the inlet speed was increased from 2 km/s to 2.5 km/s. It was experimentally established that the geometry of the combustor had a moderate effect on all the parameters, except the maximum pressure position inside the combustor, where the effect was most pronounced. However, this effect too tended to attenuate with the increase in the velocity at inlet. (T. Rolim *et al*, 2015)

Additionally, in order to maintain high performance of the engine at the operating conditions, the engine modes need to be switched by switching the ER values. For example as explained, at comparatively lower speeds and altitudes, the subsonic combustion provides more efficiency than supersonic combustion and vice versa for higher altitude and Mach numbers. The judgement of the modes is critical as the ER values for switching and other parameters depend on it. Study on judgement method of the mode of operation and operation conditions was based upon the use of computer technology, specifically neural networking to analyse and learn the patterns associated with each mode of combustion. This technology was previously successful in pattern recognition in high performance auto pilots, flight path simulations and aircraft component fault detectors. The 1D flow relations were used to determine the parameters through the engine which were used as learning cases for the neural network and established as the basis for the judgement of the mode of combustion.

8. Experimental models

In this section, some of the popular experimental models are reviewed which are typical of the most popular experimental designs that are used to simulate the operating conditions of the air-frame integrated scramjet engines.

8.1 Ground-based testing

Sullins in his experiments, made use of direct connect combustor to simulate the vehicle acceleration from Mach 5.9-6.2 by increasing the inflow total temperature. From the 1D flow analysis, it is established that the Mach number remains fairly constant across the shock wave but as the intensity of the shock wave increases, the total inflow temperature and static pressure to the combustor increases. (Heiser and Pratt, 1994) The fuel mass flow was decreased to maintain constant ER for the transition from ram mode with pre-combustion shock system in the injection plane to a scram mode where no pre-combustion shock was captured. (Z. Yang *et al*, 2014)

S. Aso *et al* used the following experimentation facility for the study of the fundamentals of supersonic combustion. The experiments have been performed in the reflected shock tunnel at Kyushu University, Japan. In the shock tunnel, test air is compressed by reflected shock wave up to stagnation pressure 0.35MPa and total temperature of 2800K. Heated air is used as a reservoir gas and provided into test section through two-dimensional supersonic nozzle of Mach number of 2. To determine the experimental conditions, measurements of total pressure and total temperature of reservoir gas were conducted. Test time in this experiment is defined as the test time of about 300 microseconds, in which the total temperature remains constant. To visualize the shock structure of the supersonic flowfield, Schlieren method has been used. The instantaneous light source of less than 1 microsecond of exposure period is used.(S. Aso *et al*, 2005).

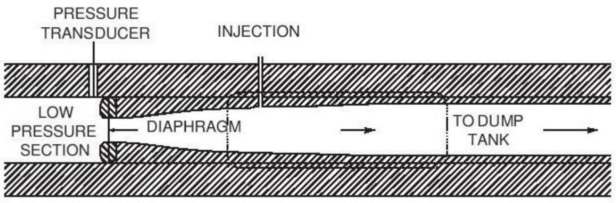

Fig. 8.1 Schematic of experimental setup used by S. Aso *et al* (S. Aso *et al*, 2005)

The operating conditions for the testing were maintained as follows.

Table 8.1 Operating Conditions in the setup used by S. Aso *et al* (S. Aso *et al*, 2005).

Property	Freestream	Injectant
Gas	Air	He, H_2
Total Pressure	0.350 MPa	0.175 MPa
		0.350 MPa
		0.525 MPa
Total Temperature	2800 K	290 K
Mach Number	2	1

Z. Yang *et al* for the investigation of the influencing factors on the mode of combustion used the experimentation facility available for dual-mode scramjet combustor in the Beihang University, China. (Z. Yang *et al*, 2014)

The vitiation tunnel conditions as are described in the operation conditions (see section 12 for Table 8.2) in the study done by Z. Yang *et al* is typical of all the vitiation tunnels used for this purpose.

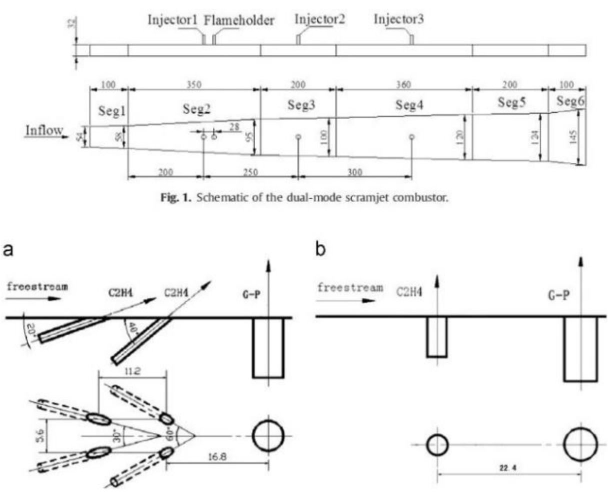

Fig 8.2 Schematic of ramp injector set up used by Z. Yang *et al* to experiment on influencing factors on dual-mode operation of scramjet engines.

The variable flow control was achieved from use of a fuel source connected to a pressure regulator which has 3 valves leading to three nozzles, which culminate in a single injector. As is evident in the figure, we can see the distribution of the injectors and their injection profiles in the 'aero-ramp' injector platform. (Z. Yang *et al*, 2014)

Q. Chen *et al* for the study on judgement methods of mode of combustion used the direct-connected facility which was specially designed for dual-mode scramjet combustor experiments. The experimental gas was heated by a vitiator, which burned hydrogen and replenished oxygen to maintain oxygen mole percentage at 21% in the experimental gas. There were two types of conditions at the entrance of isolator. There were also three types of test models, which were named as Model-1, Model-2, and Model-3 to perform experiments upon. The schematics of the test models are as shown in the schematic representation in Fig. 1. The test models consisted of isolator, combustor and nozzle. All of the three models had the same isolator. The difference in the models were the expansion angels of the combustor. The combustor of Model-1 had three expansion sections with angles of 1.5°, 2.0° and 3°. However, Model-2 and Model-3 only had two expansion sections and the angles were 1.5°, 2° and 1.5°, 3° respectively. The hydrocarbon fuel C2H4 was injected into and burned. The positions of fuel jets are as shown in Fig.1. (Q. Chen *et al*, 2013).

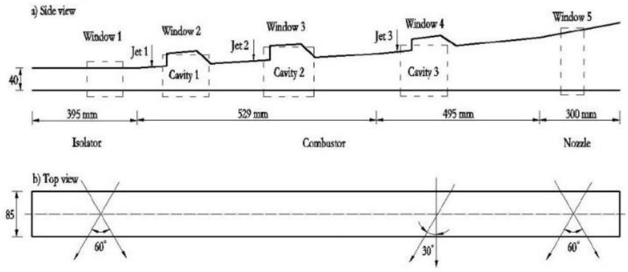

Fig 8.3 Triple model test set up used by Q.Chen *et al* for the study on judgement method of the mode of combustion of scramjet engines. (Q. Chen *et al*, 2013)

The operation parameters of the tests were kept as follows.(Q. Chen *et al*, 2013)

Table 8.3 Operation parameters sued by Q. Chen *et al* for the study on judgement method of the mode of combustion of scramjet engines. (Q. Chen *et al*, 2013)

Mach number	Total Temperature (K)	Total Pressure (MPa)	Mass ratio (kg/s)
1.8	950	0.6	1.8
2.5	1650	1.0	1.2

In the study of the judgment method for the mode of combustion of the DMSJ, by Q. Chen *et al*, the use of Radial Basis Neural (RBF) neural network was a feed-forward network with three layers based on regularization theory. A Gaussian RBF monotonically decreased with distance from the centre. So Gaussian-like RBFs were local (give a significant response only in a neighbourhood near the response only in a neighbourhood near the centre) and are more commonly used than multi-quadric-type RBFs which have a global response. They are also more biologically plausible because their response is finite. (Q. Chen *et al*, 2013)

At present, the RBF Neural network can deal well with the problem including classification and pattern discrimination. The problem of Scramjet combustion modes diagnosed belonged to the category. RBF Neural network required a supervised learning of the existing classification results, then the network would update the weights of neurons. After the learning processing was completed, the network would be able to classify the new inputs. (Q. Chen *et al*, 2013)

For the preliminary analysis of the scramjet engine experiments conducted by T. Rolim *et al* a similar popular geometry scramjet inlet with a converging inlet or 'isolator' section, a constant cross-section combustor section and a diverging nozzle section, following the relations developed for Rayleigh and Fanno flow from the 1D analysis of the flow through engine. The convergent section at the isolator provides the oblique shock wave effect and the effect of compression and decreasing the Mach number of the supersonic flow. The diffuser section increases the velocity of the products of combustion by extracting some of its heat, i.e. exhibiting an overall cooling effect on the flow of the products of combustion. This is also evident from the Rayleigh relation, which states that once in supersonic regime, the flow decelerates by heat addition and accelerates by heat extraction.(T. Rolim *et al*, 2015) (For model see in section 12, for Fig 8.4)

The research in the University of Queensland, as is documented by R. Stalker *et al*, used a reflected wave shock tunnel instead of the vitiation wind tunnels to simulate the operating conditions flow of the scramjet engine. Their shock tunnel was able to generate a hypersonic flow with velocity up to 2 km/s at 210 K total temperature and static pressure of 586 Pa. The Mach number of the flow was recorded as 6.8. Helium gas was pressurised and used to push the test gas which was air, over the test specimen. Scramjet operation ratio which is defined as the airstream kinetic energy per unit mass to that at the orbital speed if is greater than 0.1, the speeds are considered as sub-orbital speeds. Sub-orbital speeds are speeds above 2.5km/s which is achieved by adding energy to a gas very rapidly immediately before it is allowed to expand, also known as impulse techniques. The tunnels that use these techniques, namely the shock tunnels are capable of producing steady flow for a few milliseconds, thus require very high speed imaging and recording techniques to analyse the phenomena. Shock tunnel dimensions are affected by the volume of the test section - whether a component has to be tested or an integrated configuration is to be tested – as the pressure of the gas stored, i.e. the impulse generating gas is affected. (R. Stalker *et al*, 2005)

The experimentation techniques can be summarised as follows. Following the theoretical approximation of Mach number independence at high hypersonic speeds such as that of Mach 20, in ground-based testing, as there is a limitation on accelerating the flow beyond a particular Mach value, but to keep the total enthalpy of the flow constant, the temperature of the flow is increased. The velocity remains fairly constant, (the difference owed to the increased degrees of freedom to the molecules due to enhanced temperature) but the Mach number reduced drastically. (R. Stalker *et al*, 2005) However, the vitiation heated hot flows generate supersonic flow of desired velocity but a higher temperature for a long test time of the order of several seconds but due to the real gas effects of the test medium of change in properties at higher temperature such as the change in specific heats of the gas and the possible dissociation of molecule to constituent atoms or ionization of the gases, and also considerable concentration of H_2O and OH^- radicals increase the uncertainty in the validity of experimentation results, when compared with the actual operating conditions which are intended to be simulated.

Hence the impulse technique is preferred although it has a shorter test time of milliseconds as it generates a high stagnation temperature and pressure air without real gas effects by utilizing an inert gas such as He. (R. Stalker *et al*, 2005)

Shock tube, expansion tube and reflected shock tunnel are the three impulse techniques. Reflected shock tunnel provides the longest test time out of the three.(S. Aso *et al*, 2005)

8.2 Flight testing

For the actual flight testing, the Hyper-X program of the NASA's NGLT, X-43A vehicles were well instrumented, with over 200 measurements of surface pressure; over 100 thermocouples (T/C) to measure surface, structure and environmental temperatures; and discrete local strain measurements on the hot wings and tail structure. The flight management unit included a highly accurate 3axis measurement of acceleration and rates. In addition, over 500 data words were extracted from the flight computer. Instrumentation density is illustrated in Fig. by external and internal wall pressure and temperature on the lower body surface. Internal engine instrumentation on the body side is denser in order to capture internal flow details of the engine.(McClinton *et al*, 2005; R. Voland *et al*, 2006)

The overall layout of the X-43A flight vehicle is documented by V. Rausch *et al* R. Voland *et al* note that all of the data from the X-43A flights were successfully telemetered and captured by multiple air and ground stations. The instrumentation health and performance were excellent: very few lost instruments/parameters, extremely low noise content, no significant calibration issues, no significant delay or time-lag issues, and extremely limited TM drop outs. Accuracy of these measurements benefited from dayof-flight atmospheric measurements by weather balloons flights conducted prior to the flight tests. (R. Voland *et al*, 2006)

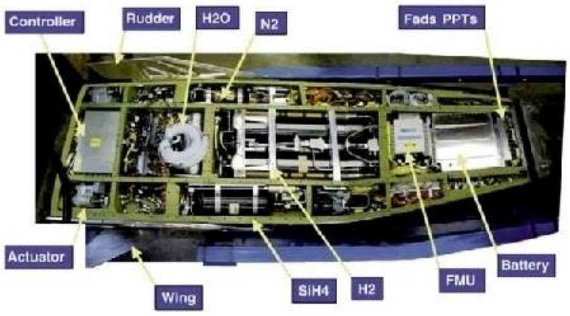

Fig 8.5 Illustration of the X-43A flight vehicle parts. (R. Voland *et al*, 2006)

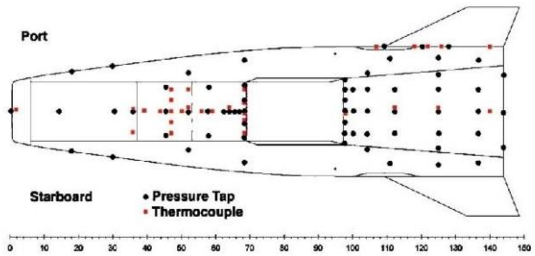

Fig 8.6 The locations of the pressure and thermocouple sensors are illustrated in the diagram. (R. Voland *et al*, 2006)

9. Performance Discussion

R. Stalker *et al* suggest that the difficulty in operations at sub-orbital velocities increase with an increase in velocity as the propulsive effect of the engine gradually decreases. (R. Stalker *et al*, 2005)

9.1 Fundamental studies of supersonic combustion

In the study conducted by S. Aso *et al* to investigate the condition of the combustion phenomena with relation to the shock structure in the flow-field, both Schlieren method and CCD UV camera were employed. In all cases, small recirculation region can be seen just upstream of the injection point. However, due to the small diameter of hole and the sensitivity of camera, the recirculation region only appeared very small. They reported further, the total pressure of injection will affect the height in crossflow. The images indicated that when the injection total pressure is increased, the bow shock formed by the injection jet becomes stronger and the angle of shock wave increases. Also the increase of total pressure of the injection jet results in the increase of total pressure loss of the flow. Additional oblique shock wave is observed in the joint part of the wall located at 72mm downstream of the injection point. The strong reaction is established after oblique shock generated by joint of wall, about 80mm downstream of the injection point and suggests that to accelerate the reaction it can be very useful using shock generator. (S. Aso *et al*, 2005)

The Schlieren images show that the increase of injection pressure generated strong bow shock, resulting in the pressure loses. The combustion begins almost at the same location for all injection total pressure cases, about 45mm downstream of the injection point, which indicates the reasonable induction time. After the oblique shock generated by joint part of the wall located at 72mm downstream from the injection point, the strong reaction is established. This demonstrates the shock generator be an effective method to accelerate the combustion. The increase of the injection total pressure raises the penetration of fuel; thus, the reaction zone expands to the centre of flow-field. Similar results are also observed in reacting flow (hydrogen injection).

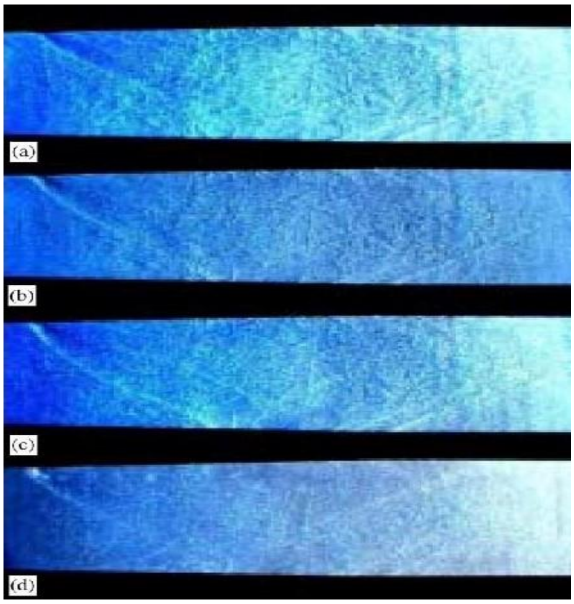

Fig 9.1 Schlieren images of flowfield: (a) Helium injection $p_{0j}/p_0 = 0.5$; (b) Helium injection $p_{0j}/p_0 = 1.0$; (c) Helium injection $p_{0j}/p_0 = 1.5$; (d) Hydrogen injection $p_{0j}/p_0 = 1.0$. (S. Aso *et al*, 2005)

However, comparing Fig. 9.1 b and d, it can be found that shock wave generated in reacting flow appeared weaker than those in non-reacting flow. This difference of shock wave strength might come from the difference of molecular weight of He and H_2. In the hydrogen combustion, the condition of the combustion can be investigated by observing the presence of OH^- radical. By recording the self-luminescence of OH^- radicals using CCD UV camera, location and intensity of the reaction zone were observed. Fig. 9.1 shows the intensified averaged image of self-luminescence of OH- radical taken by CCD UV camera and the Schlieren image of the helium injection when pressure ratio for the injection of fuel was 1.0. The reaction started at about 45mm downstream of the injection point, and grew larger as far as downstream. This distance between injection point and location of the reaction start indicates that the induction time of combustion is in the order of 10^{-5} s, thus reasonable for this experimental condition. However, the reaction cannot be found at the recirculation just upstream and downstream of the injection point. The reason may result in the poor sensitivity of the camera. The strong reaction is established after oblique shock generated by joint of wall, about 80mm downstream of the injection point and suggests that to accelerate the reaction it can be very useful using shock generator. Fig.9.2 shows the reaction zone in different case of injection total pressure (S. Aso *et al*, 2005).

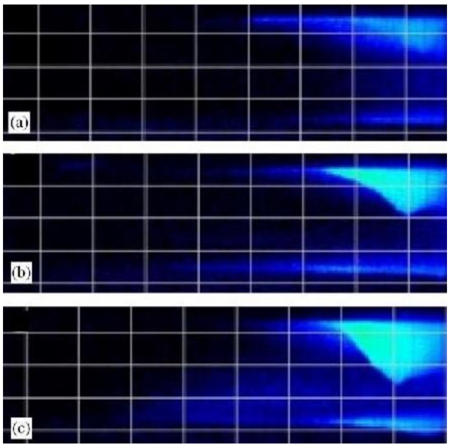

Fig 9.2 Positions of combustion reaction initiation imaged by Schlieren technique in the study conducted by S. Aso *et al* (S. Aso *et al*, 2005)

9.2 Investigation of the influencing factors and their effects on the mode of combustion

As introduced previously, the distinguishing factors between the operations of dual-mode scram mode, pure scram mode and the dual- mode ram mode can be visualized with the help of Schlieren techniques. For the pure scram mode, the results were as below, from the study conducted by Z. Yang *et al*(Z. Yang *et al*, 2014)

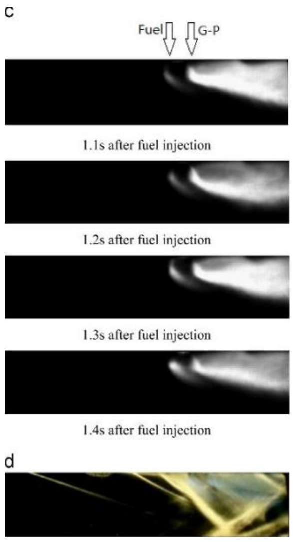

Fig 9.3 Schlieren images 'c' and color image 'd' for pure scram mode combustion as achieved by Z. Yang *et al* (Z. Yang *et al*, 2014)

For dual mode scram mode,

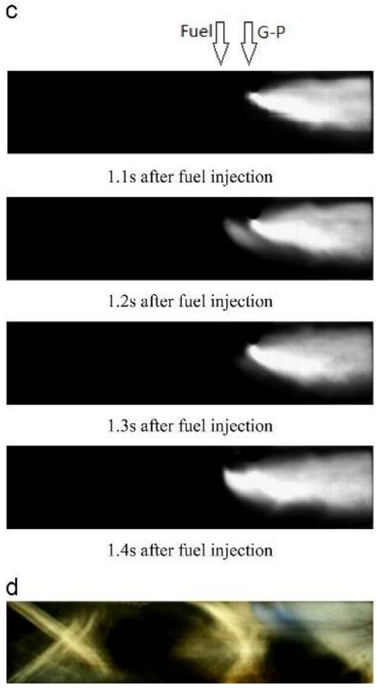

Fig 9.4 Schlieren images 'c' and color image 'd' for dual mode scram mode combustion as achieved by Z. Yang *et al* (Z. Yang *et al*, 2014)

For the dual mode ram mode,

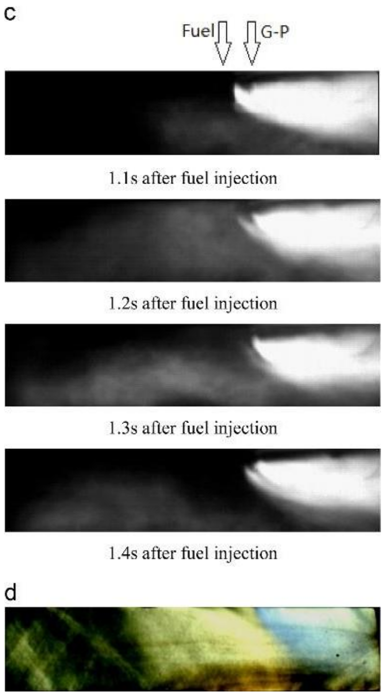

Fig 9.4 Schlieren images 'c' and color image 'd' for dual mode ram mode combustion as achieved by Z. Yang *et al* (Z. Yang *et al*, 2014)

This is evident from the flow visualizations that in the ram mode operation, there is a bright plume associated with combustion, according to the weak and intensive classification of the combustion phenomenon (Z. Yang *et al*, 2014). The region where the flow is in the un-reacting phase is clearly seen as the width from the fuel injection point and where the combustion starts. Experimental investigations have focused on the effects of increasing the inflow total temperature to simulate the vehicle acceleration while keeping the ER constant and to investigate the trend of the heat required to cause a thermally choked flow by heat addition and the trend of the ER of the fuel required for the same purpose. Z. Yang *et al* assert that the increase in inflow total temperature or the acceleration of the vehicle results in increase in the ER to cause thermally choked flow and the heat required from combustion to do so – also validated by analytical equations relating the change in Mach number to the change in total temperature of the combustion products.(Heiser and Pratt, 1994; Z. Yang *et al*, 2014) Rocci Denis *et al* suggested that larger injectors and higher injector pressures cause flow obstruction and hence ramjet operation at low ER.(Z. Yang *et al*, 2014) Takashi *et al* suggested that at low ER, the flame or mixing regions from far downstream and jumped near to the injectors with an increase in ER.(Z. Yang *et al*, 2014)

When a fixed ER is employed, the heat addition can be increased by increasing the combustion efficiency and ensuring proper mixing of the fuel-air mixture.(Z. Yang *et al*, 2014) Maddalena *et al* established experimentally that the four-hole aero-ramp has a lower mixing length than single-hole injector platform.(Z. Yang *et al*, 2014) Fotia and Driscoll established the effect of wall temperature on the combustion – lower wall temperature implies – thermal choking tendency as less heat is lost to the walls – equivalent to an effective more heat release from combustion. (Z. Yang *et al*, 2014)

In the study by Z. Yang *et al*, it was observed that the Ethylene fuel ER was greater than when Hydrogen was used as fuel for the transition critical ER values. The injector configurations have no effect on the combustor flow properties. The inflow total temp increases with increase in ER and width of the ER value between the two critical values increases. Angled injection provides ER values width larger than transverse injection. (Z. Yang *et al*, 2014) Z. Yang *et al* found that in ram mode operation – the normal shock wave at the inlet or 'isolator' was of sufficient intensity to accelerate the flow from subsonic conditions in the combustor by heat addition to sonic conditions and then the flow is accelerated through diverging duct to supersonic speeds. Although the shock waves create an adverse pressure gradient in the inlet that causes boundary layer separation, which results in increase in Mach number in the direction of the flow and the decrease in static pressure, finally causing favourable pressure gradient in the combustors. Consequently the boundary layer reattaches at the exit of the isolator and remains attached in the combustor. As the vehicle accelerates the inlet Mach number increases and the total temperature of the flow also increases – to avoid excessive temperature increase – heat release should be regulated to maintain a weak oblique shock wave that terminates in mixed features of both supersonic and subsonic flow.(Heiser and Pratt, 1994; Z. Yang *et al*, 2014) The 1D averaged Mach number at the entrance is already greater than 1 at this stage and the engine is operating in the Scram mode which is unstable and has limited range of operation.(Heiser and Pratt, 1994) Although the strength of the oblique shock weakens, there is an increase in static pressure and decrease in Mach number across the shock wave. Constant pressure combustion is expected to occur in this mode as the boundary layer creates an alternative effective wall shape. The thickness of the boundary layer in the flow direction becomes thinner thus increasing the effective flow area, causing the static pressure to decrease, which is offset by the increase in pressure due to heat addition. In the scram mode, thermal choking boundary condition is no longer applied, the heat release is not intense enough to maintain boundary separation in the isolator. Pure scram mode is characterized by no pre-combustion shock wave and the sudden pressure-rise occurs only when the reacting stage in the combustion starts, which has demonstrated the capacity to be used as a fairly accurate judgement of the modes of combustion.

Summary

The combustion modes of a dual-mode scramjet engine are classified by the pressure distributions, Mach number distributions and importantly, optical visualizations in lab environments. The transition points between the modes are influenced by fuel type (affects wall pressure distributions), injector configuration, inflow total temperature (affects transition width too), amount of fuel injected. While increase in the injection pressure can be used as a combustion accelerator due to the bow shock generated upstream of the injection point. The transition is a bi-stable system showing hysteresis as the transition points are not at the same ER values if the flight conditions such as speed are being varied in ascending and descending manner. Dual-mode operation or multi-mode operation of the scramjet engines can be utilized to maximise the thrust according to the ambient flight conditions, changing from pure ram to pure scram as the flight speed increases. Scramjet engine technology development can open the doors not only for quicker commercial atmospheric flight, but also substitute the rocket engine in the atmospheric stage of flight for better fuel efficiency.

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