

# Comprehensive Analysis of the Advanced Technologies for Scramjet

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**Abstract.** Scramjet is a kind of aspirated engine, where oxygen in the atmosphere is used as oxidant to react with fuel in fuel bunker. Structural components are used in the scramjet to generate shock waves at high speed to compress the high-speed air flow, and realize the deceleration and pressurization of the air flow, which is different from engines where air compressors are used. Technologies related to the scramjet power/fuel are presented, and the features related to this kind of engines are highlighted in this paper. The development process of the scramjets in the application field both home and abroad is overviewed. The problems involved with scramjets in hypersonic vehicle application, combined cycle power system, design of thermal protection structures and high temperature materials are discussed. The critical technologies of scramjets, i.e., tail nozzle, combustion chamber, air inlet, fuel selection etc. are identified. The features of hydrocarbon fuel and its application in hypersonic vehicles are summarized. And the progress of research of the relevant technologies and personal prospects for scramjets are briefly described.

**Keywords:** Scramjet, thermal protection structures, high temperature materials, hydrocarbon fuel.

## 1. Introduction

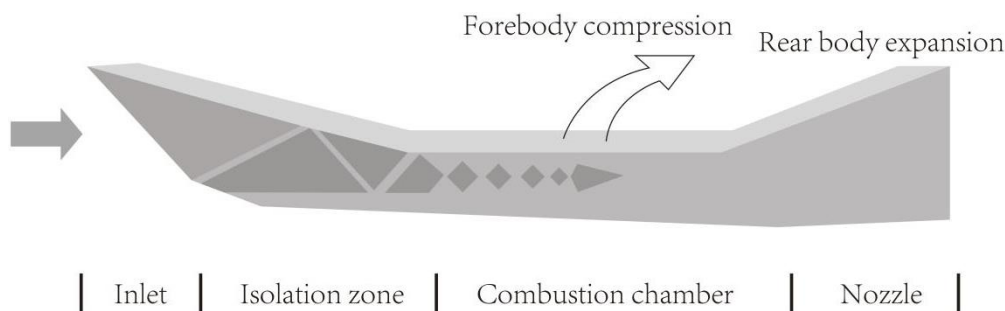
The concept of scramjet was proposed by French scientist René Lorin in 1913 and published in *Flying Wings*, which opened the way for mankind to conquer the sea of stars. During the cold war, it was also a hot research and development field in the arms race. Thanks to this, we have been witnessing a rapid development of the scramjets since the 1950s. Scramjets can continuously provide power for aircraft with a speed greater than Ma4 during high-speed cruise flight, allowing them to fly at cruise flight speed of Ma6-Ma15. Its cruise speed is much higher than that of other aircraft power systems, and its fuel specific impulse is also much higher than that of traditional rocket engines. In addition, they would allow aircraft to realize horizontal takeoff and landing and reuse based on this performance, which greatly helps reduce the transportation cost. The scramjet has been a hot research project of the world's major aviation powers. In the research and development of scramjets, we have experienced many advances and frustrations in various fields, but at the same time, we have also accumulated many valuable experiences and lessons, laying a solid foundation for the application of scramjets in the aviation and aerospace field in the future.

Scramjet is a kind of aspirated engine, where oxygen in the atmosphere is used as oxidant to react with fuel in fuel bunker. Structural components are used in the scramjet to generate shock waves at high speed to compress the high-speed air flow, and realize the deceleration and pressurization of the air flow, which is different from engines where air compressors are used.

Scramjets are used in the power system of long-range flight vehicles cruising at a speed above Ma5 within the atmosphere or trans-atmosphere, which can continue to work at around Ma12-Ma15. Although the scramjet has an excellent performance above Ma6, its structure does not support it to get sufficient oxidant and achieve ignition below Ma4, which makes it impossible for it to work effectively below Ma4. So it is necessary to mount other types of engines in the flight vehicles to accelerate to approximately Ma4. Rockets can be used as boosters for single-use flight vehicles, while more efficient combined cycle system should be used for those requiring multiple reuse and horizontal takeoff and landing. Scramjet is a critical technology for hypersonic spacecraft and its development will have a great impact on the future military strategy, weapon system building and even the whole scientific and technological progress.

## 2. Critical technologies of scramjets

Scramjet is a kind of aspirated engine, which mainly consists of air inlet, combustion chamber and tail nozzle. Oxygen in the air stream is used as an oxidant to react with the fuel in this kind of engine. Scramjet is different from turbocharged engine where active suction technology is used. Scramjet inlet needs to compress the high-speed incoming stream by using the shock wave generated during the cruise of the flight vehicle at higher Mach. The internal functional components are used to decelerate and boost the air stream and provide stable and sufficient oxidant for the burning of the subsequent fuel in the combustion chamber.



**Figure 1.** Diagram of scramjet structure.

In the actual operation of scramjet, as shown in Figure 1, the combined cycle components are used for ignition, and the inlet is used to decelerate and pressurize the high-speed incoming stream. Then the compressed incoming stream enters the combustion chamber for combustion and oxidation with the fuel to convert chemical energy into gas internal energy. Once the high energy gas enters the tail nozzle, it expands and expels the generated thrust, which is greater than the resistance of the inlet and generates an acceleration, which is an operating cycle. This cycle is called Brayton cycle [1-3].

### 2.1. Supersonic inlet technology

As one of the three subcomponents of scramjet, the inlet is integrated with other components but independent of each other. The performance and features of the inlet have a great impact on the scramjet. The inlet failure or insufficient intake will often lead to insufficient combustion of fuel in the combustion chamber, which will lead to the insufficient engine power even flameout. And the coupling degree between the inlet and other components of the flight vehicle is also a hot technology studied by scholars around the world. At present, the research carried out by the scientific community on the inlet is mainly aimed at the integration of the inlet and high-speed spacecraft.

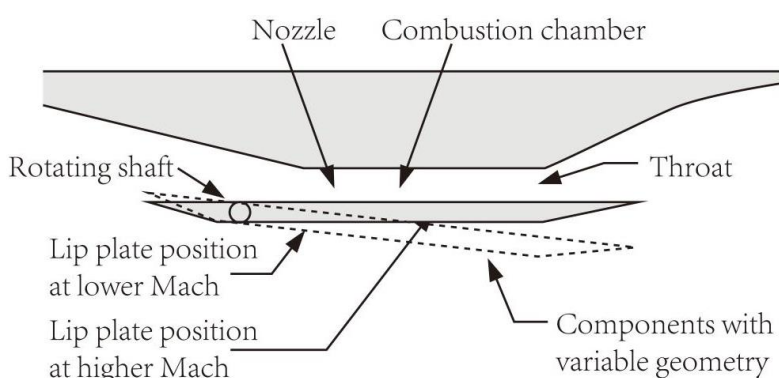
In recent years, normally four kinds of inlets are widely used in scramjets, namely, 2D planar compression inlet, axisymmetric inlet, side pressure inlet and internal contraction inlet. Axisymmetric inlets are widely used for hypersonic missiles. 2D planar compression inlet, axisymmetric inlet and internal contraction inlet are commonly used for hypersonic vehicles. [2,4,5]

#### 2.1.1. 2D compression inlet

The 2D inlet is based on the wave distribution theory. Most of the inlets are rectangular, and wedge-shaped precompression surfaces are mounted in most cases. When the air stream flows through the slope, it will be pre-compressed, and then it will achieve hypersonic compression through a series of oblique shock waves and compression waves. The air compression process of this kind of inlet only occurs in the 2D plane, so the wave system is relatively simple and easy to analyze and study. Therefore, it is easier to design the 2D inlet cover as a movable part. This kind of inlet has the advantages of simple structure and adjustable inner surface. However, the compression efficiency of this type of inlet is low due to its long compression area and strong shock wave boundary layer interaction. Thanks to the horizontal tuning plate of this type of inlet, it can be adjusted automatically at higher Mach. This type of inlet is normally used for aircraft flying at over Mach 1.5 [1,6-8]. Previously, the variable geometry 2D inlet was adopted in the French PROMETHEE project, which has a continuous adjustment function. To meet the low internal contraction ratio and improve the

startup performance of the scramjet at the relay point (Ma4), the lip plate of the inlet passage is designed to rotate around an axis in front of the throat. Under lower Mach motion, the lip plate is rotated clockwise to reduce the contraction ratio in the inlet. When the Mach number gradually increases to hypersonic speed, the lip plate will gradually return to the design point. This design has improved the flight vehicle's stability of the acceleration at low Mach-high Mach. But it is hard to manufacture the variable geometry 2D inlet due to its complicated internal structure.

Compared with the 2D inlet with constant and variable geometry, the inlet with constant geometry is more proven in technology. As shown in Figure 2, the inlet with fixed geometry compresses the incoming air stream through the front compression surface, which improves the Mach number range of the inlet to a certain extent. The inlet with fixed geometry is carried by the X-51A flight vehicle developed by the US Space Research Laboratory. The design operating Mach number of the X-51A is between Ma6 and Ma6.5 (the data in the hypersonic inlet development research literature are Ma4-Ma6) [5, 9,10].



**Figure 2.** Structure of inlet with a fixed geometry.

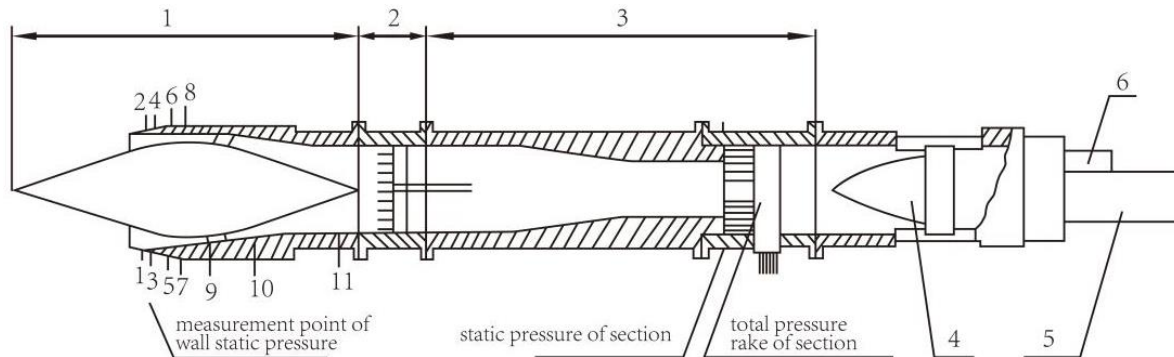
### 2.1.2. Axisymmetric inlet

Axisymmetric inlet is a kind of 2D inlet, which is widely used in the aviation and military field. It has an advantage that the axisymmetric inlet can perform isentropic compression to achieve a higher compression efficiency. It was also a hot research direction that the United States and the Soviet Union paid attention to during the cold war. The inlets used in the US HYFLY and HRE programs and the kholod program of the Soviet Union are axisymmetric inlets, which are often used in the early scramjets. Normally two types are available, the conventional hypersonic axisymmetric inlet and the dual mode axisymmetric inlet [9,10].

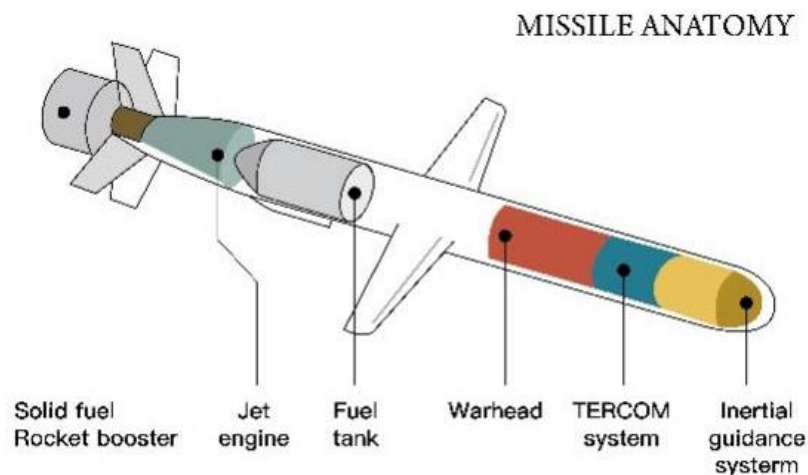
*Conventional hypersonic axisymmetric inlet:* Normally the shape of conventional axisymmetric inlet is semicircular or circular, and there is a conical precompression surface in the center of the inlet, and the position of the central cone can be adjusted back and forth, as shown in Figure 3. This design has the advantages of simple structure, relatively easy to realize variable geometry structure, less interference from incoming stream, complete data in the relevant fields etc. However, it is difficult to integrate with the flight vehicle [11,12].

*Dual mode axisymmetric inlet.* The dual mode axisymmetric inlet can work simultaneously in two operating modes, i.e. supersonic combustion and subsonic combustion. This type of inlet is mainly composed of three parts, namely, shunt divider, subsonic combustion module and supersonic combustion module. The inlet divides the incoming stream into two flow velocities during subsonic combustion. The incoming stream velocity through the subsonic module is reduced to subsonic speed and mixed with hydrocarbon fuel for combustion. The combustion products are combined with the incoming compressed stream from the supersonic combustion module, mixed again in the supersonic combustion chamber and ignited to generate high-speed expansion gas, which is then ejected. Comparing with the 2D inlet, the axisymmetric inlet has a higher compression efficiency, but the lift-drag ratio is lower. It is difficult to achieve integrated design by coupling with other accessories, so it is not suitable for hypersonic vehicles. Therefore axisymmetric inlets are mainly used in hypersonic missiles. As shown in the temporary model of FyFly in Figure 4, the dual mode inlet needs to provide

oxidant to the subsonic combustion chamber and the supersonic combustion chamber simultaneously, so this engine is equipped with six inlets, i.e. two subsonic combustion inlets and four supersonic combustion inlets. This inlet has a capability of startup at lower Mach. The startup Mach number of the vehicle is Ma3.5 and the cruise Mach number is Ma5-Ma6 [4,6,9,13].



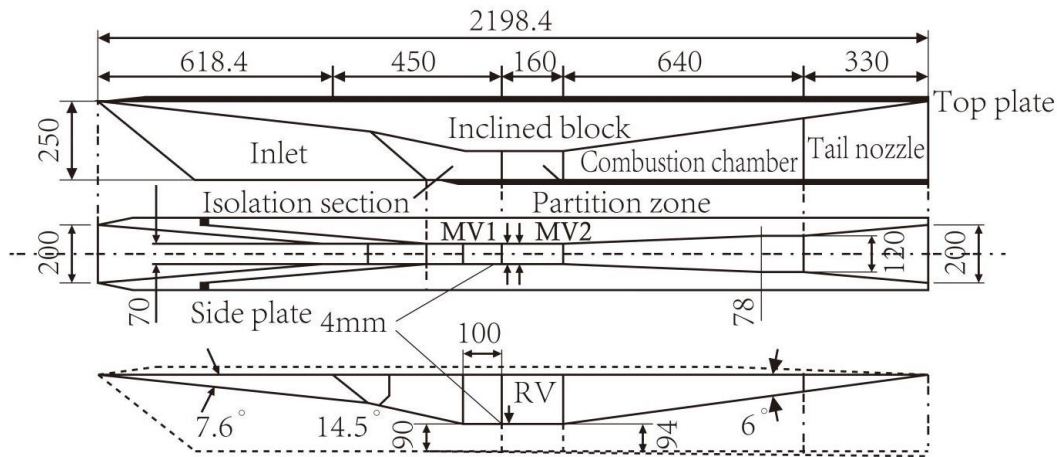
**Figure 3.** Axisymmetric inlet.



**Figure 4.** Dual mode inlets used in Tomahawk cruise missiles.

### 2.1.3. Sidewall compression inlet

The sidewall compression inlet mainly consists of forward and backward-swept side plates with compression angles, central support plate, rear lip and top plate. The supersonic incoming stream is compressed with the side plates in the horizontal direction. Thanks to the mounting of two compression surfaces, the utilization rate of the compression surface is higher than that of the 2D inlet, at the cost of the compression efficiency reduction caused by the complicated wave system. This kind of inlet has a better performance when starting at lower Mach. It is easy to modularize and has certain advantages in integrated design. However, its flow field is complicated and the interference between shock wave boundary layers is significant, which has a close positive correlation with its low flow coefficient. Despite the high compression capacity of sidewall compression inlet, its extremely complicated flow field and large total pressure loss make it hard to be applied in the hypersonic vehicles. According to the current research progress, the Kakuda Research Center in Japan has developed five series of 3D compression hypersonic sidewall compression inlets with various configurations, such as support plate compression, compression with top plate, side plate forward sweep, and mixed sweep, as showed in Figure 5. The experimental Mach number is Ma4-Ma8 after the development of sidewall compression inlets in combination with the free jet of scramjet and improvement [12,14].



**Figure 5.** Kakua 5<sup>th</sup> series inlet.

### 2.1.4. 3D internal contraction inlet

The internal contraction inlet is an internal compression inlet based on streamline and benchmark flow field technology. Both shock wave and Mach wave are used to compress for the internal contraction inlet, so it has a higher compression efficiency than other inlets. Its superior performance is favored despite its extremely complicated internal flow. According to the recent research projects, 3D internal contraction inlets are used in the hypersonic flight research experiment (HIFiRE) and HTV-3X Black Swift supersonic reconnaissance aircraft jointly carried out by the United States and Australia. There are three kinds of 3D internal contraction inlets according to the generation of internal contraction inlets, i.e. geometric transition variable cross-section internal contraction inlet, internal contraction inlet generated by direct streamline tracking and aerodynamic transition variable cross-section internal contraction inlet.

The integrated design method of forebody-internal contraction inlet is considered as an important research direction of hypersonic vehicles in the future by scholars around the world. Some American scholars used the reference flow field of the internal contraction inlet to design the wave receiver of hypersonic vehicle and obtained the shape and structure of the forebody-internal contraction inlet of integrated vehicles. The integrated configuration of the osculating-cone side forebody and the complicated inlet turning-round outlet internal contraction inlet is used for the hypersonic reconnaissance aircraft in the Falcon program conducted by the US Air Force. The design feature of this kind of vehicle is to mount internal contraction inlets on both sides of the side forebody to avoid the impact of the incoming flow of the forebody boundary layer on the inlet, which helps significantly increase the total pressure recovery coefficient. This greatly helps improve the performance of the inlet. However, the development of this kind of technology is not mature, and the aerodynamic configuration is difficult [4,7,12].

The development trend of hypersonic vehicles in the future is to fly in a wider Mach range. The combined cycle engine will be the main direction of hypersonic research and development in the future to make the hypersonic vehicle switch between supersonic and hypersonic modes more smoothly. Therefore, developing an inlet that can adapt to the dual-mode operation of combined cycle engine is the focus of the hypersonic inlet in the future. This inlet should have a good startup performance at lower Mach, and also meet the requirements of oxidant demand and total pressure recovery in hypersonic conditions

## 2.2. Combustion chamber thermal protection technology

The wave resistance of hypersonic vehicles during hypersonic cruise is large and the engine thrust margin is small. Therefore, a more appropriate aerodynamic shape must be used for the inlet to reduce the resistance. The aerodynamic heating is proportional to the cube of flight velocity and the heat flux is inversely proportional to the square root of the front edge radius when the vehicle flies at hypersonic speed in the atmosphere. It indicates that the heat load at the front end of the inlet is extremely high

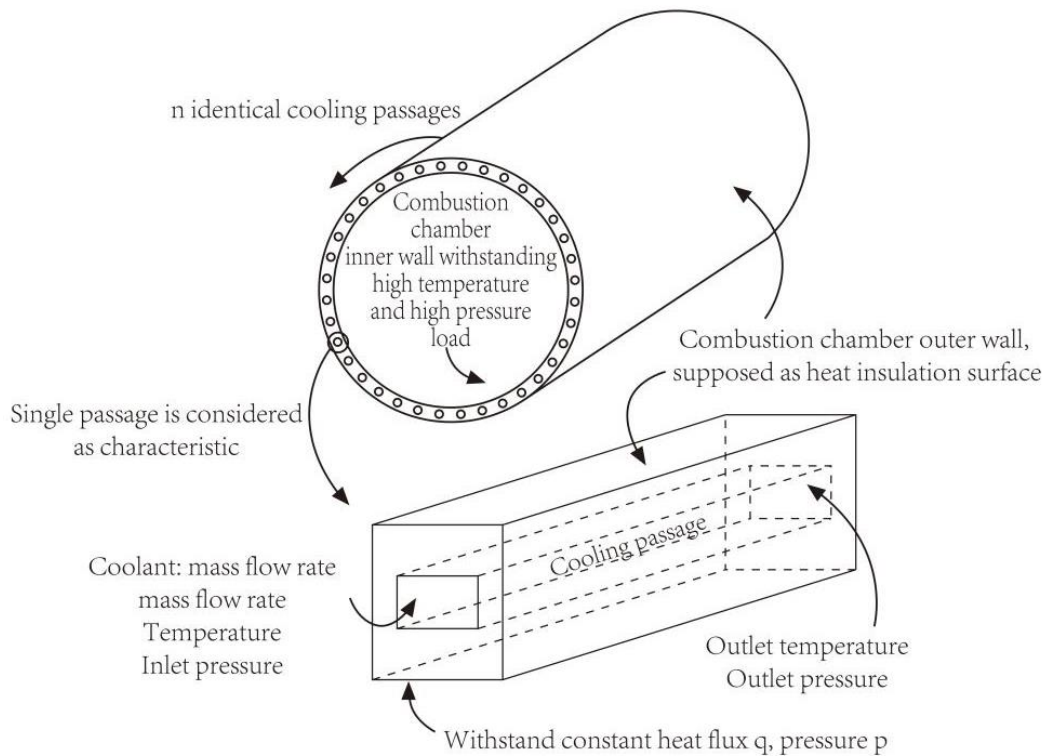
(the temperature at the front end of the inlet can reach as high as 1800K at Ma6). When the engine is operating in hypersonic mode, the internal combustion temperature is as high as (2500-3000K), and the combustion environment is characterized by oxidation. This has high requirements for the thermal protection technology of the combustion chamber of scramjets. Only the temperature at the inlet of the combustion chamber can be as high as 600k. So, the film cooling technology commonly used in aspirated engines is not applicable. There are two main thermal protection methods for scramjet combustion chambers, i.e. active thermal protection and passive thermal protection. Air flow or high flow fuel entering the engine through the inlet are used to cool the combustion chamber for the active thermal protection, while composite materials and thermal insulation coatings are used for passive thermal protection to further enhance the heat resistance of the combustion chamber and protect its components from damage, as shown in Figure 6. In this paper, five effective thermal protection technologies will be discussed, including composite technology; regenerated active; heat management; transpiration cooling, enhanced heat exchange etc. [15].

### **2.2.1. Composite technology**

Composite technology aims at improving the temperature resistance of components by changing the materials of components or the materials covering their surfaces. Composites are used as thermal protection materials for scramjets to reduce the weight of the engine and reduce the structural complexity. In recent years, ceramic materials have become a hot spot in the research of composite technology. Ceramic matrix composites (CMC) launched by NASA have advantages of low density, high heat resistance, simple production, low maintenance cost etc. CMC has successfully passed the bench test. The antioxidation temperature limit of this material can only reach 367°C, which is much lower than the design requirements of scramjets. Therefore, CMC needs to be covered with an antioxidation coating on the surface. In the subsequent study, chemical evaporation and precipitation technology is used for the CMC antioxidation coating technology. After covering the surface with SiC coating, the temperature resistance value of CMC composite reached 1727°C, which has met most of the engine design requirements [1,10,15].

### **2.2.2. Regeneration cooling technology**

Regenerative cooling technology is active thermal protection. The principle is to use the cooling channel of liquid fuel in the combustion chamber wall to absorb heat, control the temperature in the combustion chamber within an acceptable range, fully preheat the fuel when cooling the inner wall, and achieve the heat reuse. The jp-7 hydrocarbon fuel is used as the coolant of the engine combustion chamber in the X-51 experimental aircraft developed by the US Air Force. Jp-7 is injected into the front end of the engine through a fuel pump, and then flows to the rear of the engine with the stream. During the regeneration period, the fuel takes away the heat of the combustion chamber and effectively cools down the combustion chamber. When jp-7 absorbs a large amount of energy, the temperature and pressure increase and react with the catalyst on the inner wall of the pipe. Then jp-7 begins to decompose into more flammable hydrocarbon components, thus improving the combustion efficiency [16].



Structure of the combustion chamber cooling passage

**Figure 6.** Combustion chamber colling passage.

The regenerative cooling technology can only be achieved by controlling the fuel flow. If the relevant equipment is added, the engine structure will be changed, the weight will be increased and the performance will be lost. However, hydrocarbon fuel is commonly used for scramjets. As a coolant, the heat sink of hydrocarbon fuel is much lower than that of liquid hydrogen fuel. It is necessary to increase the fuel flow to achieve the cooling effect. Therefore the fuel bunkers need to be enlarged and weight increased to maintain the endurance of the vehicle, which also causes waste of fuel. To allow the fuel to have higher heat sink and have both volumetric and mass calorific values comparable to hydrocarbon fuels, the endothermic hydrocarbon fuels with physical heat absorption, pyrolysis, deoxygenation and other features and cheap and easy to obtain has become a research hot spot. When the hydrocarbon fuel acts as the coolant, if the temperature of the cooling pipe becomes too high, fouling will occur. The temperature rise range of the hydrocarbon fuel in the cooling channel can also be limited by increasing the fuel flow, but the vehicle will reduce the maximum flight Mach number. In addition, how to control the flow of the hydrocarbon fuel to match the cooling demand is also a problem [1,17,18].

### 2.2.3. Heat management technology

The concept of heat management was first proposed by NASA in 1979: "The harmful and useless capacity in the vehicle system is concentrated, dispersed or reused." The heat management indirectly improves the coolant heat sink and improves the thermal protection performance of the engine structure. The primary objective of applying heat piping in scramjets is to ensure that the temperature of all components of the engine is kept below the maximum tolerance level of materials. The secondary objective is to analyze the heating of cooling channel and inlet and optimize the relevant principles to improve the comprehensive performance of the engine. Therefore, before applying heat management to the scramjets, it is necessary to examine the heat load of its internal components, analyze the heat carrying capacity of each component, and identify thermal protection measures. American Spiritech has developed a heat exchange analysis tool dedicated to the research of scramjets. It can conduct heat exchange analysis according to the shape, size, material features and coolant elements of the engine, so as to control the coolant flow and the size of heat exchange components

without affecting the performance of the vehicle, minimize the coolant flow and heat exchanger mass. The heat exchange design is optimized to maximize the overall performance of the scramjet [9,19].

#### **2.2.4. Transpiration cooling technology**

For the engines of hypersonic vehicles above Ma10, the traditional hydrocarbon fuel can not meet the power requirements, so liquid hydrogen fuel with higher volumetric calorific value is required. Therefore most thermal protection technologies are not applicable to such vehicles at extremely high cruising speed. Transpiration cooling technology is one of the few engine thermal protection methods applicable to this cruising speed. The coolant seeps out from the heated wall surface under high pressure and flows into the combustion chamber. The cooling medium forms transpiration flow on the boundary layer, adjusts the thermal conductivity of the boundary layer on the wall, and blocks the heat transmitted from the boundary layer to the wall surface. The coolant itself also absorbs heat on the wall surface to achieve the effect of cooling the wall surface. This technology has the advantages of high cooling efficiency, low coolant mass demand, less interference with the mainstream etc. However, it has higher pressure requirements and is suitable for hypersonic vehicles. In the 1990s, NASA believed that transpiration cooling technology was a promising new technology. In subsequent research, transpiration cooling technology has been successfully used in J-2 engine and SSME injection panel. Currently, the newly developed perspiration ceramic composites have gradually received attention. This material, which is composed of high-density ceramics and low melting point metals, can absorb heat energy through metal perspiration at high temperatures. High density ceramics have higher thermal resistance, which can maintain the structural strength and aerodynamic shape of components during hypersonic cruising. [1,20-22].

#### **2.2.5. Enhanced heat exchange technology**

The principle of enhanced heat transfer technology is to set roughness on the surface of the cooling passage of the scramjet, which can enhance fluid disturbance, reduce the thickness of the bottom layer of the fluid laminar flow, achieve the heat transfer between the fluid and the wall to alleviate the local high temperature. According to the research findings, adjusting the roughness in the cooling channel of the scramjet combustion chamber can effectively reduce the coolant flow rate requirements on the wall surface. In addition, memory alloy on the combustion chamber inner wall can make it withstand the change of temperature and shock wave position inside the combustion chamber, which can generate a rough enhanced heat transfer structure, so that the wall temperature can be effectively reduced to control the high heat flow.

### **2.3. Tail nozzle technology**

There are many kinds of tail nozzles, and there are two kinds of classification at present. In the first method, they are classified into convergent nozzle and convergent-divergent nozzle according to the features of the flow channel. In the second method, they are classified into adjustable nozzle and non-adjustable nozzle according to whether the nozzle area can be changed. Adjustable convergent-divergent nozzle is widely used in hypersonic vehicles. The expansion ratio of fuel gas of this kind of tail nozzle is very large, which can minimize the thrust loss caused by incomplete gas expansion. This type of tail nozzle includes moving tail cone type, multi-regulating plate type etc. Ejector tail nozzles had been used in some hypersonic vehicles, which uses the air flow to adjust the expansion ratio of the main flow to achieve the operating purpose [7,23,24].

Scholars mainly focus on the research of the internal features and aerodynamic loads of the nozzle. In terms of the internal features, the nozzle thrust and the loss of force in the main flow, change of air leakage flow rate, cooling air and air separation loss should be considered. In terms of aerodynamic compliance, it is necessary to estimate the aerodynamic compliance of the nozzle components for the design of the structural strength of the components and the design of the aerodynamic system.

The tail nozzle has a significant impact on the performance and quality of the engine. In the future, the tail nozzle should be designed to improve the following performance, achieving post stall

maneuvers at high angles of attack, breakthrough of post stall barrier, maneuverability and agility, shorter takeoff and landing distance, improving the stealth capability etc.

## 2.4. Fuel technology

At present, hydrocarbon fuel is the main power source of scramjets. The traditional liquid hydrocarbon is basically derived from petroleum refining products. Limited by the crude oil composition, it has a maximum density of approximately 0.8g/ml and a volumetric calorific value of approximately 35 MJ/L. Artificial synthesis and fuel blending are effective ways to improve the energy property of hydrocarbon fuels, but the low-temperature performance and application performance will be significantly reduced when the fuel density exceeds 1g / ml. Adding high-energy solid particles to the fuel will allow hydrocarbon fuels to obtain more ideal theoretical energy property. Slurry fuel and energetic gel fuel technologies have been proposed to obtain higher mass calorific value and volume calorific value.

### 2.4.1. Energetic slurry fuels

In the last century, the National Advisory Committee for Aeronautics (NACA) of the United States found that adding an appropriate amount of high-energy metal ions to liquid hydrogen fuel can improve the efficiency of the vehicles. For example, boron particles can improve the flight distance of vehicles, and adding magnesium particles can significantly improve the thrust coefficient of engines [1]. Therefore, the National Advisory Committee for Aeronautics (NACA) of the United States has carried out research on adding high energy solid particles to hydrocarbon fuels. During the research, the content of solid particles added accounted for over 50% of the liquid hydrogen fuel, and it was only made into a suspended liquid by simple mixing technology. Normally the storage time of such fuels is no more than 6 months. Moreover, the slurry fuel is too dense, which will cause the droplets formed during atomization to be coarser and larger in volume than the traditional liquid hydrogen fuel. This would lead to uneven combustion and cannot meet the expected effect. And in these research results, there are cases where the storage time cannot meet the application requirements and significant solid-liquid separation occurs in a short time. In subsequent studies, scholars effectively promoted the combination between solid particles and liquid molecules through additional active agents or pretreated the surface of the particles to improve the mixing coefficient [23,25,27].

### 2.4.2. Energetic gel fuels

Gel in the energy containing gel materials is used to gelify some liquid components, and some solid fuels are added to suspend in the gelified fuel, which helps to form the fuel structural and specific performance and can extend the storage time of the fuel. According to the property of the gel fuels, they can be divided into two types, metallized gel fuel and nonmetallized gel fuel. NASA has carried out a lot of research on the metallized binary gel fuels. Oxidants commonly used in the binary gel fuel system include hydrogen peroxide, chlorine trifluoride (CTF), nitrogen tetroxide (NTO) etc. Normally, liquid hydrogen fuel, hydrocarbon fuel, etc. are selected as liquid fuel. High energy metal ions such as aluminum powder and magnesium powder are often added to the metallized gel fuels [28, 29].

## 3. Combined cycle engines

A scramjet cannot work effectively below Ma4, so it needs to be sent to the relay point with other propulsion devices. Pulse detonation engines and turbocharged engines can realize self-startup at low speed, but their performance will decrease with the increase of speed and their operating upper limit is around Ma5. So, it is necessary to develop a power system-combined cycle engine, which can realize the self-startup, reuse and powered horizontal landing of hypersonic vehicles. The combined cycle engine is composed of many different types of engines. It has combined the advantages of many different engines and has achieved optimal combination and broadened the flight Mach number range.

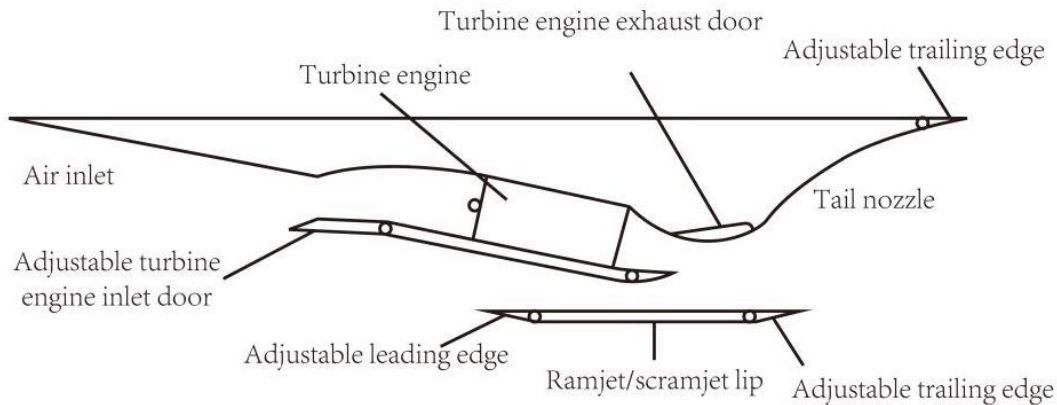
At present, combined cycle engines mainly include rocket based combined cycle (RBCC) engines, turbine based combined cycle (TBCC) power system etc.

### 3.1. Rocket-based combined cycle (RBCC)

Rocket based combined cycle (RBCC) engine is composed of rocket-based engine and aspirated engine, which constitutes an integrated propulsion system. This kind of engine has four operating modes: ejection mode, ramjet mode, scramjet mode, and pure rocket mode. The oxygen obtained from RBCC ascending stage can get more average specific impulse than that of the rocket engine. An RBCC consists of inlet, fuel blending diffuser, combustion chamber and tail nozzle. Different operating principles will be used for the engine with the rise of Mach number. RBCC enables the ejection mode to provide power for the spacecraft at Ma0-Ma3. Under the action of the high temperature gas ejected from the rocket, a large amount of air enters the mixing diffuser to mix with the fuel for combustion. In the second stage, the incoming flow pressure is low, and the thrust of the engine is mainly provided by the rocket ejector. The high temperature gas is mixed with air for afterburning, which generates thrust and accelerates the spacecraft to the next relay point. RBCC starts subsonic combustion ramjet mode at Ma3-ma6. The rocket exhaust volume gradually decreases at this stage, and the incoming flow entering from the inlet is recovered in the diffuser section. As the total pressure of the incoming flow rises, the recovered pressure can generate sufficient thrust to allow the engine to propel in the ramjet mode. The rocket ejector can be used as pilot flame when it is operating continuously at high mixing ratio and low pressure. The engine changes from ramjet mode to scramjet mode at Ma6-Ma12. The vehicle is propelled by the scramjet to the relay point MA12-Ma? The inlet is closed and the engine shifts to the pure rocket mode, when only the rocket generates thrust. Among the four operating modes of RBCC, the ejector mode is relatively less studied. At present, the problems encountered in RBCC experiments and research in the United States have shown that the ejector mode problems are the most complicated. Although scholars have obtained some observations and measurements in a number of studies and experiments, the relevant studies only remain at the level of observation and measurement.

### 3.2. Turbine-based combined cycle (TBCC)

A turbine-based combined cycle (TBCC) is a combination of dual mode ramjet and a turbine, which are commonly arranged in parallel vertically, as shown in Figure 7. The operating principle of this engine is similar to that of RBCC. the inlet of the turbine engine is activated and propelled by the turbine engine module at Ma0-Ma3. The ramjet is activated and the turbine inlet is gradually closed when reaching the relay point of Ma3-Ma6. The dual-mode ramjet starts to switch to the scramjet mode and continues to accelerate the vehicle when the speed is accelerated to approximately Ma6. The deceleration procedure is opposite to the acceleration procedure. Jet precooled TBCC is a hot research topic in recent years. The operating principle of this kind of engine is that the jet fluid in the inlet evaporates and cools the air flow in the inlet, which reduces the air temperature and the increases the incoming flow density. This technology increases the oxidant content in the engine and increases the engine thrust by approximately 15%. Experiments have indicated that the maximum speed of precooled TBCC can reach above Ma6 and has a higher thrust-weight ratio than ramjet. The problem of TBCC is that the inlet of turbocharged mode at low Mach number is relatively independent from that of dual-mode ramjet mode at high Mach number. There are fewer common parts in the inlet, which results in the reduction of the vehicle volume and the increase of the structural weight. Therefore, optimizing the component structure between turbine and ramjet modes, reducing the engine mass and improving the volume are the main development directions of TBCC in the future [1,4].



**Figure 7.** Diagram of TBCC structure.

The aircraft king with combined cycle engine as the power system has a wide flight envelope, with flight Mach numbers ranging from subsonic, transonic, supersonic to hypersonic. This is a great challenge to the engine performance. The various components (such as the intake combustion chamber and the tail nozzle) have different problems in different operating modes of the combined cycle engine system, such as the conflict between the requirements of the combustion chamber and the exhaust system. Therefore, how to make the internal structure of the combined cycle engine compact and reasonable is the difficulty in design. The combined cycle engine runs at different speeds in different modes, so some components are idle at any time. How to optimize the structural coupling is also one of the difficulties.

#### 4. Conclusion

Scramjet is the primary critical technology to achieve hypersonic vehicles. It is defined as a ramjet in which fuel burns in supersonic flow and generates thrust. The operating process of the scramjet is that the supersonic flow is diffused in the inlet at a lower supersonic speed of  $4Ma$ , and then the fuel is injected and combined with the air in the combustion chamber for combustion. Due to the energy of the air flow itself and the precompression of the inlet, it can complete the complicated design related to the turbine, to simplify the engine structure. Normally, ramjets need to decelerate and pressurize the air flow. The best solution is to reduce the residence time of high-pressure gas in the engine as far as possible to ensure that the high pressure and high temperature brought by the air flow will not exceed the limit of conventional engine materials. The cruise speed of scramjets is maintained above  $Ma5$  due to the uneven incoming flow. The configuration of combustion chamber is very important in the design process as the combustion chamber of scramjet is very complicated. Hypersonic system components are working under extremely high heat load. High-temperature resistant CMC or carbon composite materials should be used when selecting materials, and a variety of cooling technologies should be used to ensure that all components are kept within the heat load limit. The fuel also serves as a coolant in the scramjets using hydrocarbon/liquid hydrogen fuel. The flying speed is below Mach 8 when hydrocarbon fuel is used for the scramjet. The flying speed of the scramjet can reach Mach 6-25 when liquid hydrogen fuel is used. As the air flow through the scramjet is always supersonic, the air residence time in the vehicle is only a few milliseconds. It is very difficult to complete the compression, pressurization, blending and ignition in the fuel flow state in such a short time. Whether the fuel can be fully blended with the air directly affects the volume of the engine and the thermal load of components. Therefore, it is necessary to design a feasible scheme to carry out systematic analysis and experimental research on the size, shape, fuel type, injector design and combustion mechanism of the engine. In order to solve the abovementioned problems, scholars have proposed two types of engines using dual-mode ramjet and dual combustion chamber ramjet technology. The dual-mode ramjet can work in both subsonic combustion and supersonic combustion modes. The incoming flow generates a positive shock wave under the action of the inlet to achieve subsonic combustion when the cruise Mach number of the engine is below 6. Supersonic combustion

is achieved when the velocity is greater than Mach 6. This technology further increases the operating range of the vehicles and reduces the Mach lower limit of the scramjet to Ma3. The inlet of the subsonic combustion and hypersonic combustion dual combustion chamber is divided into two parts, which cut the incoming flow into two sections. The split flow flowing into the subsonic inlet is decelerated and pressurized to subsonic speed. The flow into the supersonic inlet is decelerated and pressurized but maintained at supersonic speed. The subsonic combustion chamber is operating in an oil-rich manner and serves as the ignition source of the supersonic combustion chamber. Dual mode engines are used in unmanned aircraft or conventional hypersonic vehicles owing to their reuse and wide range of cruise Mach. The ramjet and scramjet dual mode combustion chambers are widely used in cruise missiles and other disposable vehicles due to its low risk and low cost.

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