

Overview of Research Progress on Solid Rocket Ramjet Engines

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Abstract: Solid rocket ramjet engines are the ideal propulsion devices for high-speed aircraft. This article reviews the research history of solid rocket ramjet engines, analyzes the latest developments both domestically and internationally, and summarizes the key technologies that still need to be addressed in this field. These include wide-range flight inlet design, aircraft/engine integration overall technology, gas flow regulation technology, combustion organization technology, and so forth. Furthermore, it provides a summary and outlook on the future prospects of solid rocket ramjet engines, offering valuable insights for the development of related technologies in the future.

Keywords: Solid Rocket Ramjet Engine; Inlet Design; Aircraft/Engine Integration Technology; Gas Flow Regulation Technology; Combustion Organization Technology

1 Introduction

The Solid Rocket Ramjet Engine, abbreviated as SRRE or Ducted Rocket Engine, is the ideal propulsion system for next-generation high-speed aircraft. Aircraft equipped with SRRE have extended range, strong penetration capabilities, high operational reliability, rapid combat response, and excellent maneuverability, making it a research hotspot worldwide^[1-2]. The SRRE combines solid rocket engines with ramjet engines, utilizing compressed air as the oxidizer, thereby reducing the need for oxidizers in the propellant and increasing the engine's specific impulse. Compared to solid rocket engines, the specific impulse of SRRE can be increased by 3 to 5 times, significantly extending the range of missiles^[3-6].

The typical configuration of a solid rocket ramjet engine is illustrated in Figure 1, comprising components such as the inlet duct, gas generator, combustion chamber, and nozzle. The inlet duct captures a sufficient amount of air from the atmosphere and efficiently compresses it. The gas generator provides lean oxygen gas for combustion and imparts a jetting effect on the inlet duct, enhancing its performance. Within the combustion chamber, the high-speed stream of air from the inlet duct is mixed with the primary combustion products injected by the gas generator for secondary combustion. The nozzle expels the high-temperature gas into the atmosphere at a certain velocity and direction to generate the required thrust^[6-7].

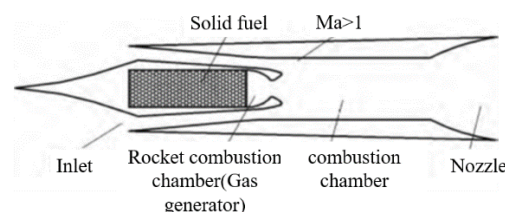


Figure 1 A typical configuration scheme for a solid rocket ramjet engine

This article reviews the research and development history of solid rocket ramjet engines, as well as the

latest research and application status both domestically and internationally. It summarizes the current key technical challenges faced, including wide-range flight inlet design, aircraft/engine integration overall design, gas flow regulation technology, and combustion organization technology, and provides an outlook on future development directions.

2 Research Dynamics at Home and Abroad

2.1 Research Dynamics Abroad

2.1.1 Application Status

Since the late 1940s, research on ramjet engines has been underway abroad. In the early stages, liquid fuel was commonly used in ramjet engines. However, with the advantages of simplicity in structure, good maneuverability, high safety, and reliable operation, solid rocket ramjet engines gradually gained significant attention from various countries, becoming an important direction for development^[2]. Starting from 1954, the American company Thiokol conducted multiple flight tests of solid rocket ramjet-powered aircraft. By the 1960s, the Soviet Union successfully developed the "SAM-6" missile, marking the first application of solid rocket ramjet engines in surface-to-air missiles. These engines achieved a maximum Mach number of 2.8 and a range of 30 to 35 kilometers, ushering in a new stage of development for the application of solid rocket ramjet engines.

In the mid-to-late 20th century, researchers in various countries successively achieved breakthroughs in key technologies of solid rocket ramjet engines, such as integral solid rocket ramjet engines, high-energy boron-containing propellants, and gas flow regulation. This sparked a surge in research on solid rocket ramjet engines^[3,8-9]. In 1976, the French company ONERA conducted two flight tests of solid rocket ramjet engines using integral solid rocket ramjet engines with a four-sided inlet layout. The range achieved was 35 kilometers. In 1982, the German company MBB conducted flight tests of solid rocket ramjet engines for the EFA experimental missile, utilizing high-energy propellant containing 40% boron. In the 1980s, the United States began developing adjustable flow integral ramjet engine technology for medium-range air-to-air missile BVRAAM. Test missiles used high-energy, low-smoke propellants containing boron, and inlet duct simulated test conditions at 3.25 Mach.

Since the beginning of the 21st century, the United States has undertaken various missile projects powered by solid rocket ramjet engines, including the supersonic sea-skimming target missile "Coyote", the High-Speed Anti-Radiation Missile (HSAD), and the Triple Target Terminator Missile (T3)^[10-12]. The European "Meteor" air-to-air missile entered the flight testing phase in 2006, completed its development in 2008, and began equipping the armed forces. "Meteor" utilizes a flow-adjustable gas generator and features a dual lower-side binary pressure-inlet layout, significantly expanding the attack envelope of air-to-air missiles. It can achieve a maximum flight speed of up to Mach 4.0 and has a range exceeding 100 kilometers^[13].



Figure 2 Meteor air-to-air missile

Currently, the United States and the Norwegian company Nammo are collaborating on a project called "Tactical High-speed Offensive Ramjet-Extended Range" (THOR-ER). The engine used in this project is a solid ramjet engine. Two flight tests were completed in August 2022, with the second phase of flight testing scheduled for the fall of 2024. On July 11, 2016, the Swedish Air Force announced the official deployment of the Meteor missile on the Gripen fighter aircraft. This missile represents the most advanced technology in its class, with a specific impulse of up to 9,000 N·s/kg and a combustion efficiency of up to 92%^[13-15]. Since 2015, Russia has been implementing the "Cheetah" plan, a medium- to long-term development plan extending to 2030 with a maximum Mach number of over 12. Currently, over 100 domestic research units are involved in relevant research and development efforts.

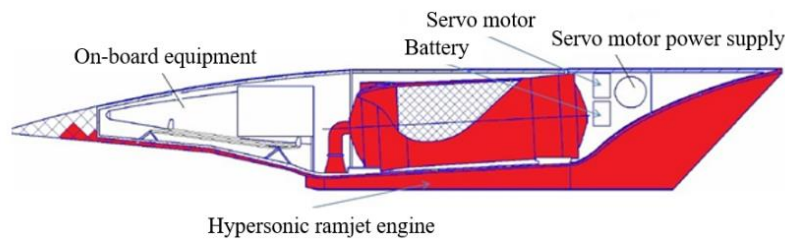


Figure 3 Russian "Cheetah" aircraft

Nowadays, research on solid rocket ramjet engine technology has also followed the mainstream trend and development direction of various countries in developing miniaturized high-speed aircraft. This trend poses higher requirements for the size and performance of ramjet engines^[15-16]. In early 2020, the US Navy proposed the development of a hypersonic cruise missile smaller in size than HAWC (Hypersonic Air-breathing Weapon Concept) to accommodate mounting on aircraft such as the F/A-18 and to meet the maintenance requirements aboard ships. On November 2, 2020, Russia initiated the development of a land-based, medium-range, small hypersonic missile weapon project called "Klevok-D2". The feasibility analysis of this project focuses on the solid rocket ramjet engine and its integration into the missile's design. The missile is designed to travel at speeds of Mach 5 and is capable of destroying targets such as enemy headquarters, command posts, artillery, and armored vehicles located up to 100 kilometers away in a short period. It is expected to enter service around 2030^[17].



Figure 4 "Klevok-D2" Schematic diagram

2.1.2 Research Status

After decades of research and development, significant achievements have been made in the technology of ramjet engine inlets. The current high-speed inlet configurations can be categorized into different types based

on the compression method, including two-dimensional compression, side compression, and three-dimensional internal compression^[18-20]. Two-dimensional compression often utilizes multiple compression wedges or local curved surfaces to form external compression. In the design state, the multiple oblique shocks generated by the multi-stage wedges or surfaces intersect at the inlet lip, where the lip and wedges form the internal contraction section. This design allows for various geometric adjustments and is suitable for high-speed flight. Side compression inlets, on the other hand, utilize compression on both sides to further increase the inlet contraction ratio. They can automatically spill over at the inlet lip with changes in Mach number, making them suitable for wide-speed range flight. Additionally, their rectangular inlet cross-section facilitates integrated design with the aircraft fuselage. Internal compression inlets include both straight-line traced internal compression inlets and variable-area internal compression inlets. The compression process is completed entirely within the duct, resulting in higher compression efficiency and total pressure recovery coefficient. This has attracted widespread attention from researchers. The U.S. Air Force Laboratory proposed the Jaw three-dimensional internal compression inlet and obtained a thrust gain of 24.87% through simulation analysis, demonstrating the development potential of internal compression inlets.

Gas flow regulation technology began in the 1990s and has been developed for over 30 years. Currently, the mainstream adjustment schemes for variable flow gas generators include the vortex valve method, variable throat area method, and non-choking method^[13-14,21-24]. Currently, the solid rocket ramjet engine of the German "Meteor" missile employs closed-loop control of the gas generator pressure, with a flow modulation ratio of 10:1 to 12:1. Japanese scholar Hisahiro Nakayama and others have developed a high-temperature rotary valve-type flow control device for solid rocket ramjet engines and conducted thermal tests.

In the research on combustion organization technology, researchers have established two types of physical models for the combustion heat release of oxygen-deficient solid propellants. Oxygen-deficient solid propellants containing boron are also gradually entering engineering applications^[25-30]. Foreign scholars have proposed several methods to improve the ignition and combustion performance of boron-based propellants. These include substituting boron with metal borides to optimize the propellant formulation, as well as using easily combustible metals or fluorine-containing compounds, surface coating of boron particles, using energetic binders, and agglomeration of boron powder granules. These methods show promising application prospects. Additionally, research has indicated that optimizing injection structures and flow control device configurations can also enhance the mixing of gases with high-speed air and improve combustion efficiency.

2.2 Domestic Research and Development Dynamics

The research and development of solid rocket ramjet engine technology in China began in the 1970s. In the mid-1980s, China conducted its first domestic solid rocket ramjet engine flight test by replicating the "SAM-6". Subsequently, the development phase shifted towards gas flow adjustable solid rocket ramjet engines. In November 2010, the National University of Defense Technology completed China's first domestic flight test of a gas flow adjustable solid rocket ramjet engine. Since then, multiple flight tests of gas flow adjustable solid rocket ramjet engines have been conducted. Concurrently, China has conducted extensive research in areas such as inlet optimization, combustion theory, and integrated design.

In terms of inlet optimization, researchers such as Wang Yi, Liu^[31-32], based on a simplified binary high-speed inlet model, found that the lip angle has a significant impact on the inlet performance. By moving the shoulder point of the inlet aft and adjusting the lip compression angle, the starting performance of the two-

dimensional inlet can be improved. Xu Shangcheng, et al. [33], incorporated appropriate Bump-type surfaces into the integrated configuration, altering the lateral spillage within the inlet, and reducing the inlet starting Mach number, as shown in Figure 5. Wang Jianyong, et al. [34], introduced reflux channels into the integrated structure, facilitating the transfer of low-energy airflow in the separation zone, thus lowering the self-starting Mach number of the inlet, as shown in Figure 6.

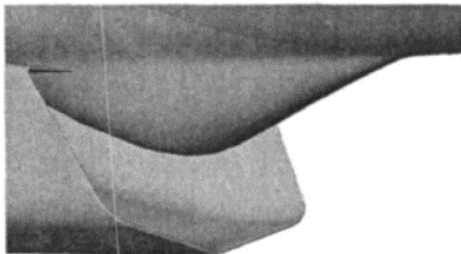


Figure 5 Bump inlet

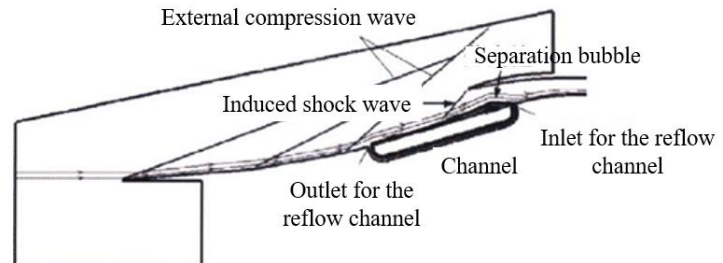


Figure 6 Reflow device

In the research on combustion theory, Lv Zhong, et al., through experimental and numerical studies, demonstrated that magnesium-based metal fuel with a metal content of 50% can self-sustain combustion in the gas generator. The resulting rich-burn gas exhibits high secondary combustion efficiency^[6,35]. Li Xuan, and others from the 41st Institute of the Fourth Academy of China Aerospace Science and Technology Corporation, conducted numerical simulations of the combustion chamber flow field for the engine configuration shown in Figure 7. They demonstrated that the addition of flow disturbance devices can enhance the mixing of primary gas with air, thereby improving combustion efficiency^[25,36]. Li Chaolong, et al., conducted experiments to validate that flow disturbance devices such as inclined splitting, concave cavities, baffles, and their combination methods can effectively maintain the ignition and flame stability of rich-burn gases^[37].

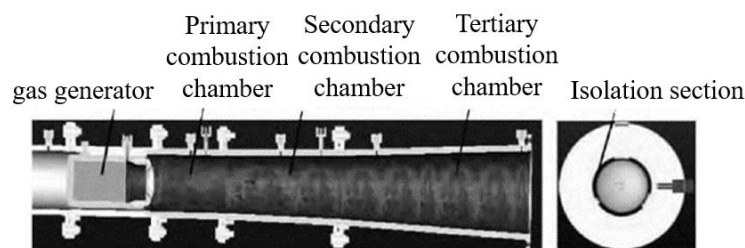


Figure 7 Solid Rocket Ramjet Engine Configuration

In terms of integrated design, Xiong Bing developed an optimization method for internal turning inlets with controllable contraction ratio based on traditional streamline tracing technology. He constructed an integrated solution with an axisymmetric body and belly/dual-sided inlet layout, as shown in Figures 8 (a, b). This approach provides a new perspective for the practical development of integrated design for high-speed aircraft^[38-39]. Li Y and others further developed the integrated design of double oblique shock bodies and double internal oblique shock inlets. They extended the theory of cone-shaped noses, incorporating the inlet into the design scope of shock bodies, thereby enriching the theory of integrated design for the internal and external flow of aircraft^[40-41].

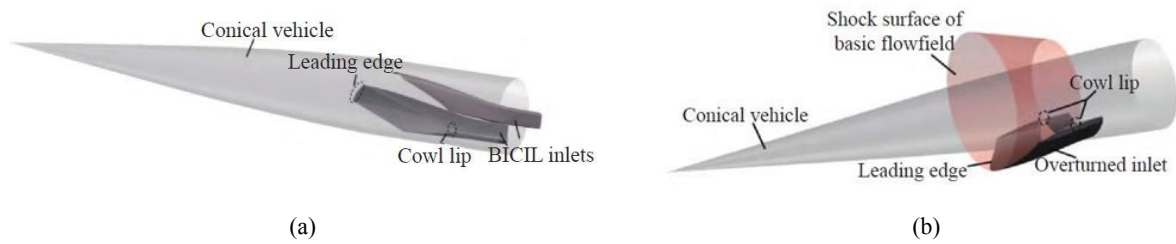


Figure 8 Integrated Design Scheme of Axisymmetric Fuselage - Belly/Dual Side Intake Configuration

3 Key Technologies of Solid Rocket Ramjet Engines

With the increasing attention on solid rocket ramjet engines, various technologies that previously constrained engine performance have gradually been overcome, entering the stage of engineering trials and model applications. To further enhance the performance and application scope of solid rocket ramjet engines, it is necessary to break through the following key technologies: wide-range flight inlet design, integrated design of aircraft/engine, gas flow regulation technology, and combustion organization technology.

3.1 Wide-Range Flight Inlet Design

The inlet is one of the key components of a ramjet engine. It utilizes its own structure to compress and decelerate the high-speed incoming airflow to the working range of the combustion chamber. This allows the inlet to capture the required airflow and maintain its quality for efficient compression, ensuring the stable and reliable operation of the engine. The main performance parameters of a high-speed inlet include compression efficiency, total pressure recovery, starting performance, airflow capture capability, resistance characteristics, and anti-back pressure performance. The performance of the inlet is crucial for the normal operation of the engine and even for the stable flight of the entire aircraft^[42-43].

Optimization design of the inlet involves reducing flow separation, improving shock/boundary layer interference, enhancing inlet starting performance, and increasing airflow and total pressure. Commonly used methods for inlet optimization in recent years include configuration optimization and increasing structural and injection energy^[44]. Configuration optimization involves adjusting and modifying the original configuration using various optimization algorithms or design parameter adjustments to enhance the starting performance of the inlet. For example, adjusting the lip angle of the lip shroud to weaken the intensity of the lip shock wave, thereby reducing flow losses in the contraction section. Increasing structure refers to adding features such as bleed slots, boundary layer suction devices, bump surfaces, reflux channels, and variable geometry control mechanisms to the geometric configuration of the aircraft. These features can remove or strip away low-energy airflow entering the inlet, improving inlet quality. Energy injection involves injecting high-energy jet streams into the inlet to disrupt the existing wave composition structure and control the flow field of the inlet, thereby improving the starting performance of the inlet. This method can be applied to high-speed two-dimensional and three-dimensional contracting inlets.

In addition, the use of variable geometry for inlet/exhaust can also expand the operational envelope of solid rocket ramjet engines, meeting the demands for airflow and compression efficiency in a wide range of altitudes and speeds. This effectively enhances the long-range penetration capability of missiles and has become a hot topic in the research and development of solid rocket ramjet engine technology.

3.2 Integrated Design of Aircraft/Engine

The structural design of the engine can significantly impact the aerodynamic performance of the aircraft, and conversely, the aerodynamic layout of the aircraft can affect the thrust performance of the engine. To meet increasingly demanding aircraft mission requirements, it is necessary to conduct integrated design between the ramjet engine and the aircraft. This involves balancing other overall requirements of the aircraft while ensuring efficient inlet and exhaust of the engine^[15,45].

The integrated design of aircraft/engine primarily involves the integration of the aircraft nose and the engine inlet duct, as well as the integration of the aircraft aft body and the engine exhaust nozzle^[46]. The layout and performance of the inlet duct are coupled with the mission characteristics, aerodynamic properties, and power system performance of the aircraft and must be considered comprehensively. The design of the exhaust nozzle must ensure maximum thrust within dimensional constraints while also minimizing the generation of excessive pitching moments due to lift acting on the lower surface of the aft body and perpendicular to the flight direction, as well as reducing aerodynamic interference between the exhaust jet and the external flow field.

In recent years, a series of innovative concepts for nose, inlet duct, and exhaust nozzle designs have been proposed, greatly enriching the theory of integrated design. For example, the concept of a dual-crest nose/inlet duct integrated configuration designs the inlet duct layout while designing the shock wave body. By using a combination of numerical simulations and experimental validation, true internal and external flow integration design is achieved. The introduction of the full shock wave concept demonstrates that integration has gradually shifted from pursuing the optimal local performance of the nose/inlet duct to pursuing the optimal overall performance^[38-39,45].

3.3 Gas Flow Regulation Technology

In order to ensure the optimal operational state of ramjet engines for diverse combat missions requiring flight in large airspace and at high speeds, gas generators with flow control valves are typically employed. This allows the engine to operate at the optimal air-fuel ratio, facilitating complete combustion in the combustion chamber and achieving maximum operational efficiency. Therefore, gas flow control technology is a crucial factor affecting the engine's acceleration capability and widening its operational envelope. Present methods for regulating gas flow include variable throat area adjustment, variable fuel surface adjustment, and variable fuel speed adjustment. Among these, the variable throat area adjustment method holds the most research value and application prospects^[14].

Currently, China has made significant progress in flow control technology, but there still exists a certain gap compared to foreign counterparts. The challenges in flow control technology primarily lie in two aspects. Firstly, the design and selection of materials for flow control devices need to meet requirements for excellent thermal protection, high strength, and strong sealing properties. Secondly, controlling the flow poses another challenge. The control system must perform closed-loop control of pressure within the gas generator, suppress the inherent negative flow regulation phenomenon, and prevent issues such as flameout in the combustion chamber and failure of the intake duct to start^[14,47]. In addition, the regulating performance of flow control devices is closely related to the composition formula and pressure index of the oxygen-deficient propellant. Therefore, it is necessary to consider multiple factors comprehensively to address the issue of gas flow control and ensure the normal operation of the engine.

3.4 Combustion Organization Technology

Efficient combustion of rich-burning gas in supersonic combustion chambers is crucial for determining engine performance. Compared to traditional solid rocket engines, solid rocket ramjet engines operate for longer durations and are constrained by propellant volume, especially for small-sized missiles with strict dimensional envelopes. Therefore, there is a need to explore high-energy-density formulations for oxygen-deficient solid propellants, such as incorporating boron-based additives into the propellant. However, ignition difficulties and low combustion efficiency are encountered with boron particle additives, posing higher demands on the development of new high-energy oxygen-deficient solid propellants, including research into modifications for boron particles^[25].

Furthermore, to enhance the secondary combustion efficiency of rich-burning gas in the combustion chamber, researchers employ experimental and numerical simulation methods to refine the processes and mechanisms of gas-solid two-phase combustion mixing. They optimize the internal flow passage configuration and combustion chamber structure of the engine, improve rich-burning gas injection technology, and explore combustion organization strategies for solid rocket supercombustion ramjet engines. These efforts aim to expand the operational range and performance of wideband engines^[25-27,48-49].

4 Summary

Solid rocket ramjet engines, as a new type of propulsion system, have become an important direction for the development of advanced power technologies in the future. Its application prospects are very broad, and it has gradually become a relatively independent field of power technology. China's solid rocket ramjet engine technology has a good foundation, and many key technologies are being gradually overcome, ushering in rare opportunities for development. In the future, research can be further strengthened in the following areas:

(1) Enhance the integrated numerical simulation research of the entire aircraft components and the entire flow field. Current integrated research still mainly focuses on the integrated optimization of local structures and flow fields. For the internal flow field model of the engine, dimensional reduction processing is often conducted, and even the combustion process may be neglected, with only consideration given to the aerodynamic properties of the engine. There is relatively less research on aircraft/engine integrated design based on global coupling of internal and external flow fields.

(2) Prioritize the research on the dynamic performance during engine staging to ensure its reliability. Fully simulate the working environment of the staging mechanism, such as temperature and pressure variations, to comprehensively assess the reliability of engine staging. Develop multiple staging mechanism options to meet various engine design requirements.

(3) Developing wide-range adjustable inlet/exhaust technology to broaden the engine's operating Mach number range is crucial. Compared to traditional inlets, adjustable inlets offer better low-speed starting performance and greater maneuverability. Vigorous efforts in research on integrated performance/structural adjustable inlets and nozzles, as well as integrated performance/control, can better meet the requirements of high-speed aircraft for wide-ranging flight. This area holds tremendous development potential.

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