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Progress and challenges in exploration of powder fueled ramjets

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ABSTRACT

The powder fueled ramjet is a developing propulsion system, which makes use of metal powder as the propellant and presents noticeable advantages, for instance, high specific impulse and density-specific impulse, thrust adjustment, simple structure, and suitability for high Mach flight vehicles. In this paper, the basic work characteristics are introduced and the exploration progress is reviewed and summarized for powder fueled ramjets. Furthermore, several key technologies are proposed, which mainly include the powder feeding system, ignition and combustion processes of the powder fuel, combustion organization technology, multiple start, thrust adjustment, and thermal protection technology. The development of the powder fueled ramjet is in the proof-of-concept stage, and a large number of individual technology breakthroughs have been achieved in subsonic conditions. However, in both subsonic and supersonic conditions, the combustion mechanism of powder fuel needs to be investigated by high precision gas–solid two-phase numerical simulation methods, and ground tests, thus, to guide combustion chamber design. In order to achieve thrust regulation, coupling studies on powder fuel delivery and combustion are required. Besides, new thermal protection schemes based on the lattice structural and supercritical fluid active cooling have great potential to meet the demands of complicated two-phase combustion thermal environments.

1. Introduction

Hypersonic vehicles have broad application prospects in national defense and space transportation [1,2]. In recent years, high Mach number and wide domain have become the main research direction for the development of hypersonic vehicles [3,4]. Power device, as the main component for a hypersonic vehicle, is the key technology that performs an important role in the development of hypersonic vehicles. At present, liquid fueled ramjets are the primary form of power device for hypersonic vehicles, which are widely applied in the engineering field. For instance, the flight tests of X-43A [5] and X-51A [6] both used liquid fueled ramjets, both of which belong to the Hyper-X program of the United States. Liquid fueled ramjets are capable of precise fuel flow regulation and high combustion efficiency, which are suitable for hypersonic flight environments. However, the low density of liquid fuel, the dissociation of liquid fuel at a high Mach number, the poor combustion stability, and the complex engine structure greatly limit the application of this type of power device [7–9]. Solid fueled ramjets, fueled by solid propellant, are an interesting option for ramjets. Compared with liquid fueled ramjets, it has relatively simple structures, lightened weight, high density-specific impulse, low cost, good security, and short combat response time [10]. Therefore, research on solid fueled ramjets has drawn much attention in recent years [11].

The state-of-the-art concept of powder fueled ramjets is inherited from solid fueled ramjets. Particularly, the description of powder fueled ramjet in this paper implies both subsonic combustion ramjet and supersonic combustion ramjet. The frequently used fuel of powder fueled ramjets is the high-energy powder, for instance, magnesium, aluminum, boron, and their mixture. Essentially, powder fueled ramjets are a kind of solid fueled ramjets and adopted the high-speed incoming air, water, or carbon dioxide (on Mars) in the environment as oxidizers, which are captured and compressed by a well-designed inlet [12]. Generally, the aggregate of discrete particles less than 1 mm in diameter is called powder, a substance between solid and fluid, which is solid in micro and can be treated as fluid in macro [13]. This property makes it has a strong throttling ability, which facilitates the shutdown and flow rate control of fuel conveying. The storage form of powder fuel is solid particles with high ambient temperature adaptability for long-term management and immediate response. At the same time, the powder propellant storage is isolated from the combustion chamber with high safety. The initial

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condition of powder combustion is a gas–solid two-phase dispersion pattern, so the negative impact of particle agglomeration is reduced, and particle mixing and combustion effect are significantly improved.

Table 1 illustrates the performance parameters of the commonly employed powder fuel, including the heat production per fuel unit mass H_W, per fuel unit volume H_V, melting point T_M and boiling point T_B. Table 2 shows the properties of their oxidation products. Boron powder has a high combustion heat and is an abundant source, but it generates a liquid film of B_2O_3 with a high boiling point during combustion, which prevents the internal boron from burning sufficiently. Therefore, the application of boron powder alone in powder fueled ramjets suffers from high ignition energy and low combustion efficiency, so it requires improvement to become an ideal powder propellant. The oxygen consumption of aluminum powder and magnesium powder is low, so the propellant can get high specific impulse and density specific impulse with good combustion performance by using them as fuel. They are also abundant in raw materials and at a low cost. In summary, aluminum powder and magnesium powder are the more desirable powder fuel in the early stage of powder fueled ramjets development.

Powder fueled ramjets have distinct advantages in terms of performance as listed below [16–19]:

(1) Powder fueled ramjets have a high specific impulse and density-specific impulse, due to the high energy calorific value and volumetric calorific value of the powder fuel.
(2) Fuel for powder fueled ramjets is a solid powder at room temperature. Compared with solid propellants in the form of conventional pillars, it does not exist the storage aging problem and the cost is significantly reduced. Additionally, powder fuel is more resistant to sensitivity than solid propellants, thus improving its safety and stability during manufacture, storage, and use.
(3) Powder fuel flows in the form of gas–solid two-phase under the action of fluidized gas, so it has strong flow rate regulation, which makes the powder fueled ramjet have the function of re-ignition and adjustable thrust.
(4) As the Mach number of the hypersonic vehicle increases, the temperature of the air entering the combustion chamber rises continuously, and the high-temperature combustion products of hydrocarbon fuel used in conventional scramjet are prone to dissociation, resulting in a rapid decrease of the specific impulse. However, powder fuel will not appear such problems at high temperatures, and even in the hypersonic flight state, the energy still can be fully released.

According to the method of powder fuel combustion organization, there are two types of powder fueled ramjets. Fig. 1 illustrates the schematic of powder fueled ramjets with the supersonic combustion form. One is the powder fueled ramjet without a precombustion chamber, as shown in Fig. 1(a). The powdered fuel is injected directly into the combustion chamber through the powder feed system and mixed with the ram air compressed by the inlet. Furthermore, powder fuel is burned in the supersonic airflow to produce high-temperature gas, which expands and accelerates through the tail nozzle to produce thrust. The other type is the powder fueled ramjet with a precombustion chamber, as presented in Fig. 1(b), and the powder feed system transports the powder fuel into the precombustion chamber which reacts with the self-contained oxidizer. The high temperature enriched fuel gas produced by the combustion enters the supersonic combustion chamber and is mixed with the supersonic air for secondary combustion. Subsequently, the high-temperature gas is ejected from the nozzle to generate thrust.

Table 2
Oxidation products [15].

Element	Density (g/m^3)	T_M/K	T_B/K
MgO	3.58	3073	3853
Al_2O_3	3.97	2327	3800
B_2O_3	2.46	733	2123

It can be seen that powder fueled ramjets have great development potential and broad application prospects due to their advantages. This paper provides a detailed overview of the research progress of powder fueled ramjets, discusses its key technologies, and thus summarizes the major basic scientific issues and technical difficulties faced in the powder fueled ramjets. Finally, the findings and research implications are summarized.

2. Exploration progress of powder fueled ramjet

The concept of a ramjet fueled by metal particles was proposed by American researchers as early as the 1950 s. Theoretically, it is observed that the variable which has the greatest impact on both the heat addition and the overall ramjet design is temperature. As the flight speed and inlet air temperature increase, less temperature rise is obtained for a given increase in energy, because more and more energy is absorbed by the dissociation of the combustion products [20]. Nevertheless, as the flight speed increases in the hypersonic range, the loss of engine thrust due to dissociation will become more and more pronounced. In response to these problems, the degree of reduction in combustion chamber temperature rise with increasing flight speed can be mitigated by using fuel that forms stable products of combustion. Obviously, metal fuel or fuel containing metal can form stable combustion products, which are not subject to dissociation and exist in a condensed phase [21]. Accordingly, the concept of ramjet fueled by metal particles is oriented toward the higher-speed aircraft, which would make a significant impact on hypersonic propulsion technology. The development process of powder fueled ramjets is shown in Fig. 2.

In 1951, Branstetter et al. [22] conducted an experimental investigation to determine the combustion properties of aluminum as fuel for use in high-speed aircraft. Through experiments, steady combustion was obtained with the aluminum injected in particle form, which demonstrated the feasibility of aluminum particles as ramjet fuel for the first time. At that time, the overall development level of the flight vehicle had low requirements for power devices, and other forms of engines could meet the mission objectives. Although the concept of the hypersonic vehicle has been proposed, which is still in the conceptual research stage, the key technologies are yet to be broken. In addition, the powder fueled ramjets involved numerous key technologies, which were difficult to carry out research work at the technology level at that time. For these reasons, the research on powder fueled ramjets was slow and even put on hold for a while.

With the great progress in hypersonic vehicle technology in recent years, Mars exploration has gradually become a new field of research. Therefore, the powder fueled ramjets attract people's attention again and offer a wide range of application prospects. In 2001, Goroshion et al. [23] proposed the concept of a hypersonic ramjet fueled by powdered

Table 1
Powder fuel parameters [14].

Element	Molecular mass	Combustion heat (kJ/kg)	H_W (MJ/kg)	H_V (MJ/dm^3)	T_M/K	T_B/K
Mg	24.31	25,205	25	43	923	1390
Al	26.98	30,480	31	84	933	2740
B	10.81	58,280	58	136	2450	3931

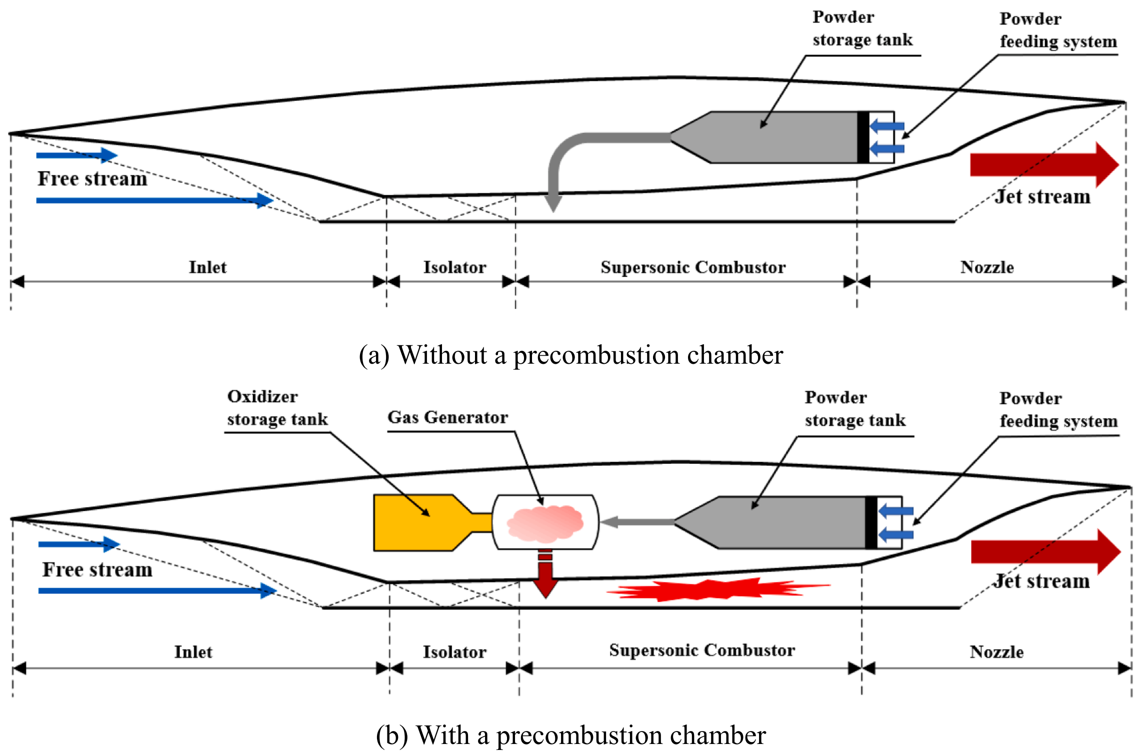


Fig. 1. Schematic of powder fueled ramjets.

metals (B, Al, Mg, and MgB_2), and the schematic illustration of the combustor was presented in Fig. 2. Since the effective operation of the powder fueled ramjet started at supersonic speeds exceeding Mach = 2, it could be easily achieved with the help of a conventional solid rocket motor that was initially integrated with the ramjet combustion chamber (Fig. 3(a)). In addition, the combustion heat release, specific impulse, and volumetric specific impulse of various powder fuels were compared through thermodynamic calculation, which showed that metal fuel could exceed hydrocarbon fuel in volumetric energy content.

In 2002, Malinin et al. [24] designed an experimental reactor for the technological combustion of metals in air, as shown in Fig. 4. The powder feeding system served to supply specified amounts of aluminum powder to the precombustion chamber, where the powder was mixed with the primary air while the air-gas mixture ignites and burns. The role of the combustion chamber was to mix the ignited metal-air mixture (supplied from the precombustion chamber) with the secondary air, burn the secondary mixture that was formed, and synthesize the oxide with specific properties. Finally, the sampler collected condensed metal oxides from a two-phase high-temperature stream (exiting from the nozzle). The experimental results illustrate that the combustion characteristics of the fuel-rich mixture make sure the reliable ignition and stable combustion of metal fuel in combustion chambers with different parameters (air-to-fuel ratio, pressure, and flow rate). Moreover, the configuration with a precombustion chamber and dual air intake designed by them became one of the main configurations of powder fueled ramjets afterward.

The French Aerospace Lab (ONERA) [25] has carried out the ground principal test of ϕ200 mm powder fueled ramjet, pointing out that the precise supply of powder fuel is one of the key technologies. However, the powder feeding system requires an additional fluidized gas source, which increases the structural complexity of the powder fueled ramjet. Based on the Martian atmosphere, Linnell and Miller [26] proposed the concept of a magnesium-based fueled ramjet for Mars exploration. Through theoretical analysis and preliminary design, they observed that magnesium was the ideal fuel by comparing a variety of metal fuels, and CO_2 in the Martian atmosphere as an oxidizer. Meanwhile, due to the low concentration of CO_2 on the surface of Mars, it is necessary to solve many technical problems, such as the low-pressure ignition of powder fuel and the compression of air intake.

The National University of Defense Technology in China has conducted exploratory experimental and numerical investigations on the powder fueled ramjet. Shen et al. [27] carried out the thermodynamic calculations and theoretical performance analyses of powder fueled ramjets, which showed that the powder fueled ramjets still have outstanding theoretical performance advantages, even taking into account the extreme loss of combustion and deposition. A summary of calculated conditions was listed in Table 3. The variation of engine specific impulse and volume specific impulse with air–fuel ratio was depicted in Fig. 5. It can be observed that the liquid fueled ramjet has the highest specific impulse when the air–fuel ratio is large, while the volumetric specific impulse is quite low. This is because kerosene has the advantage of a high mass calorific value, but the density is small, resulting in a low-density calorific value. The ducted rocket is much lower than the powder fueled ramjet fueled by aluminum in both specific impulse and volume specific impulse. Therefore, the advantages of powder fueled ramjets will be obvious when the engine volume is strictly limited. Besides, a further experimental investigation of the ignition starts and self-sustaining combustion of magnesium-based powder fueled ramjet was performed [31].

Xia et al. [32] made a comprehensive experimental investigation on the aluminum-based powder fueled ramjet, which achieved ignition and self-sustaining combustion, but the combustion deposition phenomenon was severe. Additionally, the low-frequency oscillation combustion phenomenon was analyzed and eliminated by increasing the injection pressure drop of fuel. Subsequently, in terms of the combustion chamber configuration, Kong et al. [33] designed a standing vortex flame stabilizer and verified the feasibility of the standing vortex magnesium-based powder fueled ramjet ignition through experiments. Moreover, the effects of primary and secondary air intake modes and ratios on engine ignition, combustion deposition, and combustion efficiency were investigated by numerical simulation. Yang et al. [34–36] conducted theoretical and experimental research on one-dimensional magnesium

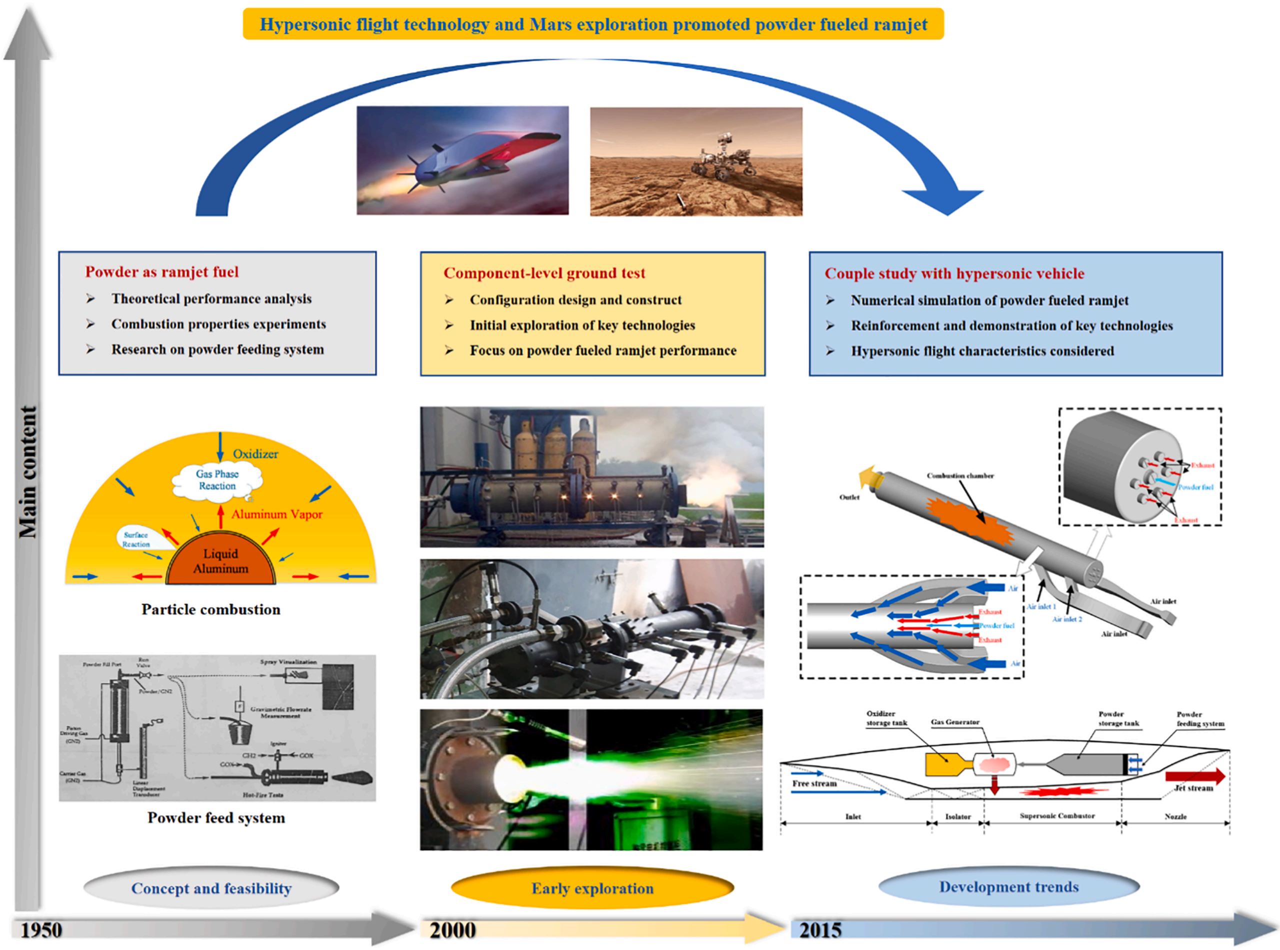
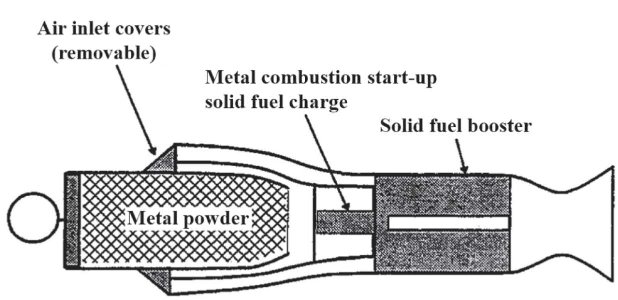
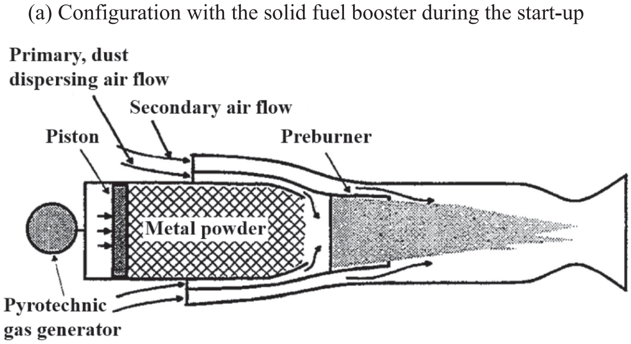


Fig. 2. Development process of powder fueled ramjets.



(a) Configuration with the solid fuel booster during the start-up



(b) Configuration during the cruise

Fig. 3. Schematic of the conceptual design of a powder fueled ramjet [23].

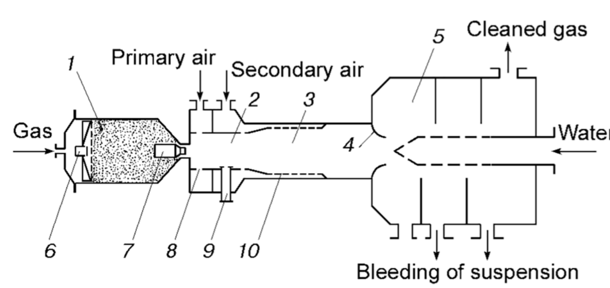


Fig. 4. Schematic of the aluminum powder/air combustion experimental reactor [24]. (1) Metal powder feed system, (2) precombustion chamber, (3) nozzle combustion, (4 and 5) sampler for collecting dispersed oxides from two-phase high-temperature flow, (6) piston valve, (7) locking and regulating valve, (8) primary air distributor, (9) igniter, and (10) secondary air distribution.

dust cloud laminar flow combustion for self-sustained stable combustion technology of powder fuel ramjet. They established a one-dimensional laminar flow premixed combustion model for the magnesium dust cloud and developed a testbed for flame propagation of dust cloud flow.

At the Israel Institute of Technology, Saraf [37] simulated the operation of a powder fueled ramjet at Mach = 3 on a ground-based direct-connected test stand. The ignition and stable combustion can be achieved by using aluminum powder and magnesium powder as fuel. The results show that aluminum powder fuel can significantly improve the specific thrust and specific impulse of the engine. Matsibeker et al. [38] studied the flow field in the combustion chamber of aluminum powder and developed a theoretical model of the combustor considering

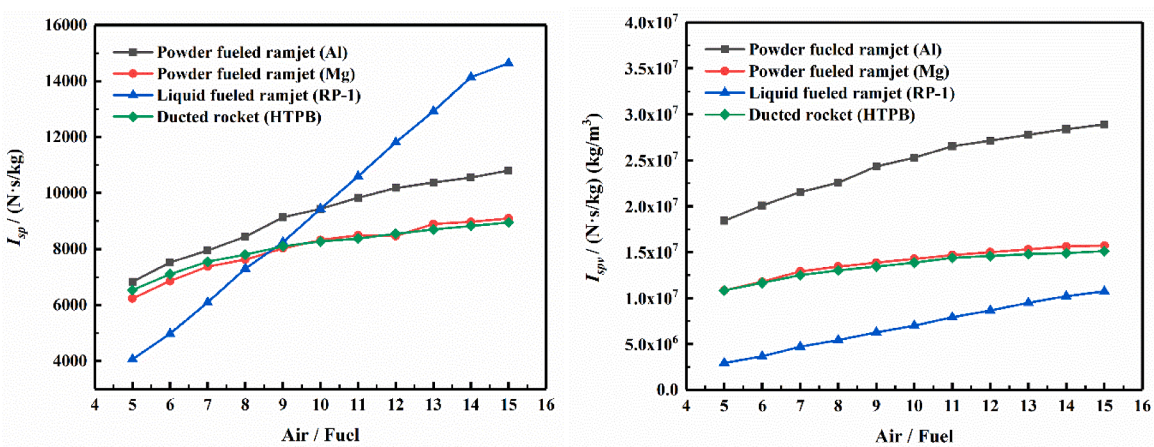
Table 3
Fuel property of the ramjet in examples [27–30].

Engine		Density (g/cm^3)	Loading density (g/cm^3)	Stoichiometric ratio
Powder fueled ramjet	Boron	2.34	0.94	9.59
	Aluminum	2.70	1.08	3.84
	Magnesium	1.74	0.70	2.84
Liquid fueled ramjet	JP-10	0.94	/	14.79
	RP-1	0.76		
Ducted Rocket	Al-35%, Mg-5% NH_4CLO_4-35%, TPB-25%	1.7	/	4.45

Remark: Flight speed Ma = 3, flight altitude H = 10 km, combustion chamber pressure Pc = 0.57 MPa.

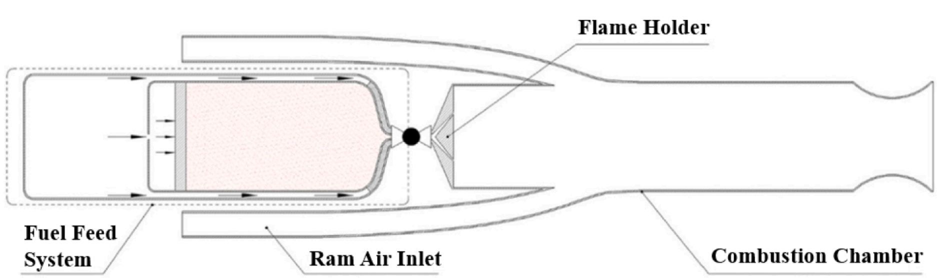
the coupling between the pulsating combustion of gel fuel droplets and the combustion of aluminum particles. They numerically solved the model using CFD to add aluminum particles separately from the fuel droplets downstream of the fuel injection. The results show that the calculated temperature field in the combustion chamber is quite smooth, and the periodic combustion of the droplets would slightly reduce the temperature of the combustor.

Li et al. [15] from Northwestern Polytechnical University commissioned a detailed study on the operating characteristics of the powder fueled ramjet, as shown in Fig. 6. A typical configuration of the powder fueled ramjet without a precombustion chamber was employed by them (Fig. 6(a)), where the powder fuel was transported into the combustion chamber and then mixed directly with ram air for combustion. Highly efficient ignition of aluminum powder fuel was achieved by using a plasma igniter. Furthermore, the effects of different air inlet positions and fluidized gas-to-solid ratios on the operating characteristics of the powder fueled ramjet was also obtained. Fig. 7 demonstrates the depositing in the combustion chamber after the hot test, which indicated that the main deposited product is aluminum solidification.

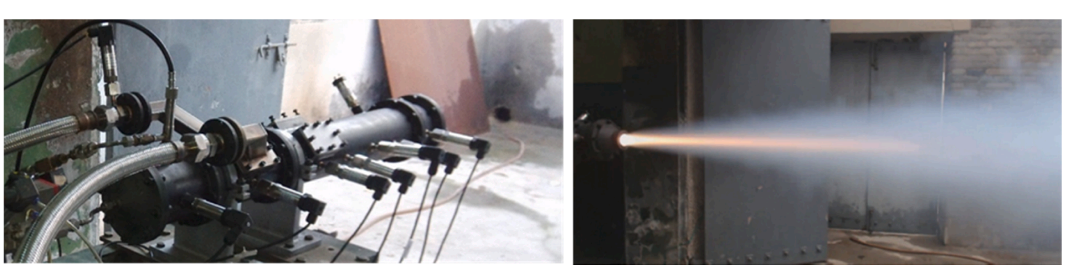


(a) Specific impulse (b) Volume specific impulse

Fig. 5. Engine specific impulse and volume specific impulse with air–fuel ratio [27].



(a) Configuration of the powder fueled ramjet



(b) Hot test of the powder fueled ramjet

Fig. 6. Schematic of the powder fueled ramjet test [15].

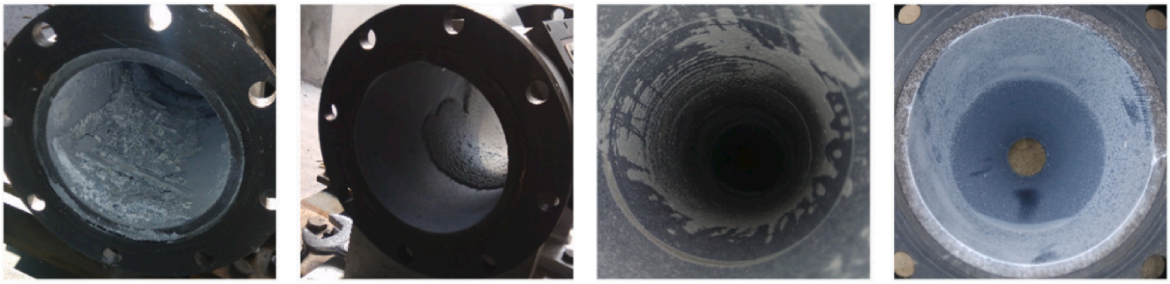


Fig. 7. Deposited product of the hot test [15].

Based on previous research achievements in powder fueled ramjets, the concept of powder fuel combined ramjet engine was presented in recent years, which was reflected in the form of fuel combinations and engine configurations. Ma et al. [39] proposed a new ramjet engine configuration based on a solid/powder fuel combination, which was fueled by boron powder particles and adopted a secondary air intake. The primary air intake ensures that the air–fuel ratio is nearly the equivalent value, which meets the requirements of engine start-up and stable combustion. The secondary air intake increases the air–fuel ratio of the engine, which is conducive to the specific impulse of the engine and avoids the phenomenon of gas temperature reduction caused by a large amount of air concentrated in the engine head. Whereafter, Xu et al. [40] designed a new ramjet configuration using powder and solid fuel as the propellant, namely, hybrid powder-solid ramjet (HPSR), as shown in Fig. 8. The solid powder is injected from the head of the second combustion chamber and burned in the combustion chamber, increasing the operating temperature and total pressure, thus improving the engine performance. Combustion gas from the generator enters the second combustion chamber with the powder fuel, mixes with the ramming air, and burns at high temperatures to produce gas, which is discharged from the engine nozzle to generate thrust.

By retrospective reviewing exploration of powder fueled ramjets, it is evident that the powder fueled ramjets have obvious performance superiority and broad application prospects in the hypersonic vehicle. The technical feasibility of powder fueled ramjets has been demonstrated by ground tests, theoretical calculations, as well as numerical simulations. However, powder fueled ramjets are still in the proof-of-concept stage, including the preliminary demonstration of a single technology and the exploration of new technologies. Meanwhile, its research mainly focuses on the ground test and theoretical calculation of performance, without conducting flight tests. In recent years, the hypersonic vehicle with higher flight speed (Mach = 8 or higher) has become a research hotspot, and its power device faces more severe challenges.

3. Key technologies

3.1. Powder feeding system of combustion chamber

As the core component of powder fueled ramjets, the powder feeding system has been the research focus and difficulty. Due to the powder particles in the discrete solid phase, there is no fluidity, so the corresponding flow carrier is needed to realize powder transportation. In 1970, Fricke [41] first put forward the powder feed system using gas as the flowing carrier of powder propellant, which was later applied by a number of researchers to design powder feed systems corresponding to different types of engines. In order to maintain the same density of powder fuel in the tank, the usual method is to add pistons in the tank, which are exerted to push the powder forward to fill the gap left by the output powder. According to the piston driving mode, the powder fuel feeding system can be divided into the pneumatic driven piston and motor driven piston respectively.

3.1.1. Pneumatic driven piston

Pneumatic driven piston powder feed system is also called the forward displacement fluidized bed powder feed system, which adopts gas-driven pistons to achieve stable powder bed transportation. The powder feeding structure is more compact and the negative mass of the system is smaller.

Loftus et al. [42] of Bell Aerospace employed a propellant feed system similar to the industrial fluidized bed when conducting feasibility verification tests on powder engines, as shown in Fig. 9. The powder feeding system uses air pressure to drive the piston and then push the powder forward, and the piston end has a uniform distribution of small holes, the fluidized gas in the piston guide rod through the small holes of

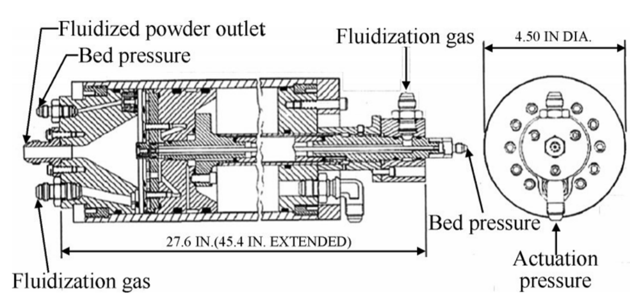


Fig. 9. Fluidized bed powder feed system [42].

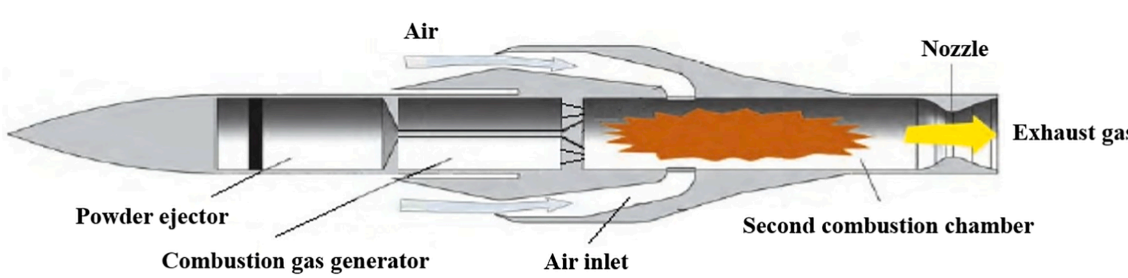


Fig. 8. Schematic of the hybrid powder-solid ramjet [40].

the piston end into the powder layer to fluidize the powder output. To prevent powder accumulation in the convergence section, a first-class gas path is added to the convergence structure. Moreover, the powder propellant loading rate is a crucial aspect of power feed system research, which can reach up to 76% through particle size grading and other methods. A fluidized bed-type powder feed system can achieve stable delivery of powder propellant, but due to the complex structure of the system, it is not conducive to the integration of powder engine systems and lightweight applications.

Meyer [43] has improved the fluidized bed powder feed system for metal powder/air engines. The improved powder feed system (Fig. 10) simplifies the piston structure, the fluidized air inlet channel inside the piston rod is directly connected to the air holes at the end of the piston, which are sintered with a purple copper muffler cover, which prevents the powder from backflowing into the fluidized air inlet channel. Meanwhile, for the purpose of decreasing the powder near the cylinder wall into the piston seal and thus increasing the live friction resistance, it has added a nitrile rubber bowl at the leading edge of the piston to sweep the powder near the cylinder wall.

Foote et al. [44] enhanced the structure of the more complex fluidized bed powder feed system into a positive displacement fluidized bed. Unlike the powder feed system designed by Loftus and Meyer, it eliminates the need to drill a fluidized air inlet through a piston guide rod, and instead uses a collection chamber and a porous metal plate. By making the piston and the head of the tank into a concave structure and welding a porous metal plate to it, the fluidized gas is firstly collected in the gas collection chamber and then passed through the porous metal plate into the powder layer. Moreover, the guide rod of the piston is connected to another cylinder, through the movement of the piston in the cylinder to drive the piston in the storage box, and this driving method can ensure that the piston movement has a good coaxially. However, the additional cylinder is not only unfavorable to the overall integration of the engine but also increases the engine mass.

Compared with the above-mentioned types of powder feeding systems, the fluidized air intake mode of the powder feeding system designed by Miller et al. [45] takes place a great change, which is unique in that the fluidized gas is transported into the powder layer by hose, as shown in Fig. 11. Owing to that the hose can be bent and stretched at will, it can follow the piston to move together, and the control of each hose is independent. By controlling the pneumatic valve, the size and speed of the fluidized air volume in any hose can be realized, which is convenient for the stable adjustment of the pressure in the powder storage box. Meanwhile, an air replenishment road is added at the powder outlet to balance the pressure in the storage box. However, the disadvantage of this method is that the length of the hose is consistent with the stroke of the piston, and the hose needs to be coiled in the storage box in advance. A larger stroke of the piston will lead to the hose occupying a larger space in the storage box, thus reducing the powder loading rate.

Li et al. [15] designed a more simple and efficient pneumatic driven piston powder feed system for powder fueled ramjet, as displayed in Fig. 12. The head of the powder feeding system is designed as a conical structure while taking into account that the powder is easy to accumulate in the head of the storage tank under the push of the piston, so the fluidized gas inlet position is set on the conical convergence section, and the fluidized inlet position is closer to the powder outlet, which is in favor of the fluidized transport of powder. By adjusting the flow rate of the drive gas and fluidized gas, the piston movement, stable powder delivery, and flow rate can be realized, and the powder delivery can be shut down by controlling the opening and closing of the ball valve. The system has been validated in a large number of powder feeding tests of Al/AP powder rocket engine, aluminum powder ramjet, and Mg/CO_2 powder rocket engine.

3.1.2. Motor driven piston

The powder feeding system of the motor drive piston adopts the drive cavity and fluidized cavity connected with the pipeline powder feed to keep the pressure difference at both ends of the piston relatively stable. Through the motor driven piston movement to achieve powder feed, its system pipeline is relatively simple, and thrust adjustment operation is relatively less difficult, while the negative mass is larger, the requirement of engine system integration is higher. The powder feeding system of pneumatic driven piston enables the powder flow rate to regulate flexibly. Whereas the gas is a compressible fluid, the air pressure on both sides of the piston tends to fluctuate, which may lead to unstable motion of the piston.

In order to make the piston move smoothly in the tank, Goroshin et al. [23] came up with the use of a motor to drive the piston. Due to the connection of the piston rod and the electric pole, pole motorsports corresponding drive the piston movement, and the rate of movement of the piston can be controlled by adjusting the motor speed, to realize smooth piston movement. Subsequently, Goroshin et al. [46] designed the convergence section of the storage box as a circular slot intake structure, and the fluidized gas entering from the circular slot structure

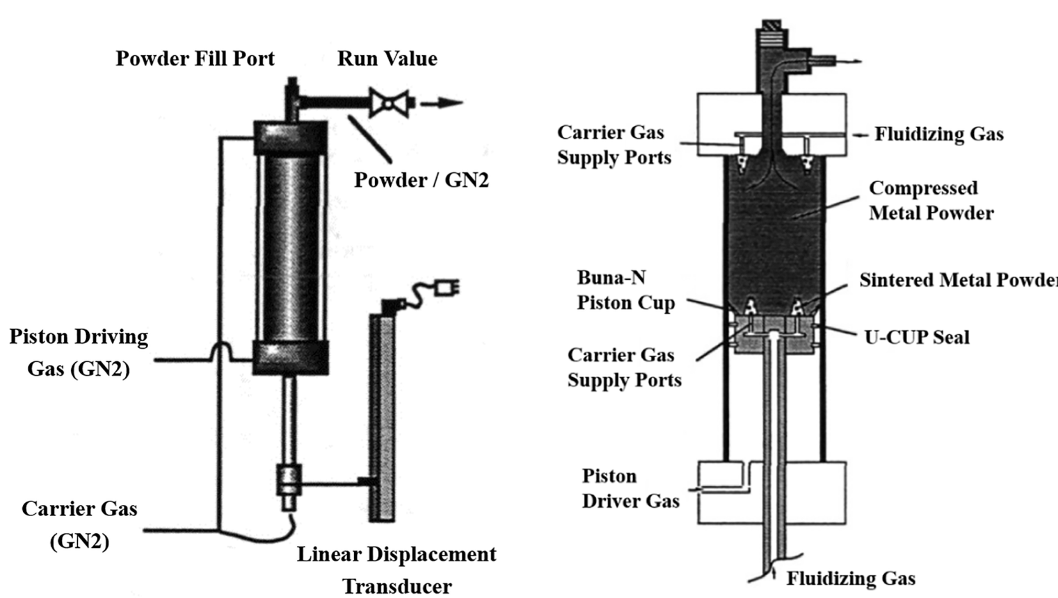
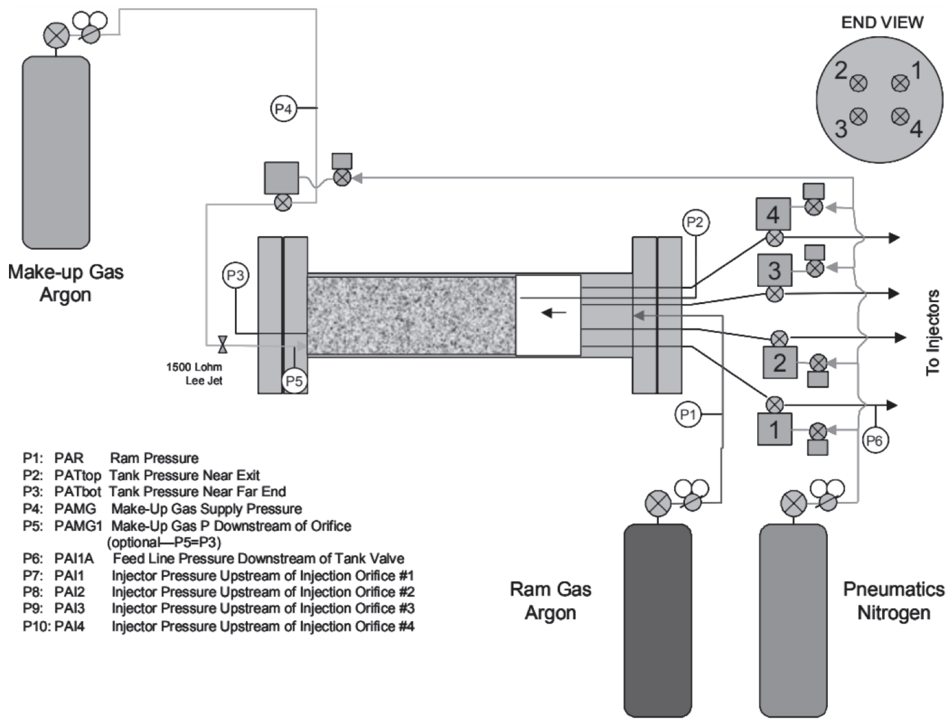
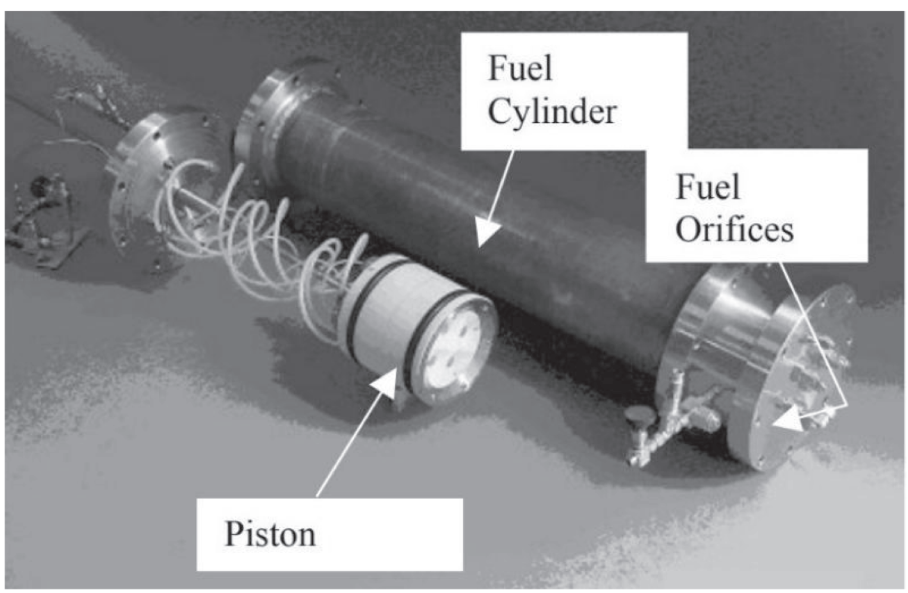


Fig. 10. Powder feed system of the pneumatic driven piston [43].



(a) Composition of the powder feed system



(b) Photograph of the powder feed assembly

Fig. 11. Schematic of the powder feed system [45].

can carry and start the powder particles flowing through here, and then flow through the scaling channel to enhance gas–solid mixing and increase the flow velocity. Moreover, the annular air intake has little effect on the structure of the powder layer.

The fuel feed system was designed by Shen et al. [47] for the powder fueled ramjet also belongs to the motor driven piston, which differs from Goroshin's design in that the fluidized gas annular slit inlet is replaced by an annular gas collection chamber structure. Since the engine is usually placed horizontally during ground tests, the lower part of the ring slit structure is easily blocked by powder under the influence of gravity, which affects the entrance of the fluidized gas, while the gas flow velocity is faster in the ring collection chamber, and the turbulence of powder particles entering the fluidized area is enhanced by the action of fluidized gas, which is less likely to deposit and block the fluidized gas inlet hole.

The powder feeding system of motor driven piston is also one of the fuel feed methods for powder engine research at Northwestern Polytechnical University [48]. The system structure is the same as it is designed by Shen et al., with the difference that the powder blending section has an additional powder dispersion structure at the outlet to facilitate efficient combustion of powder fuel. Sun et al. [49,50] have carried out a series of studies on powder propellant transport and its

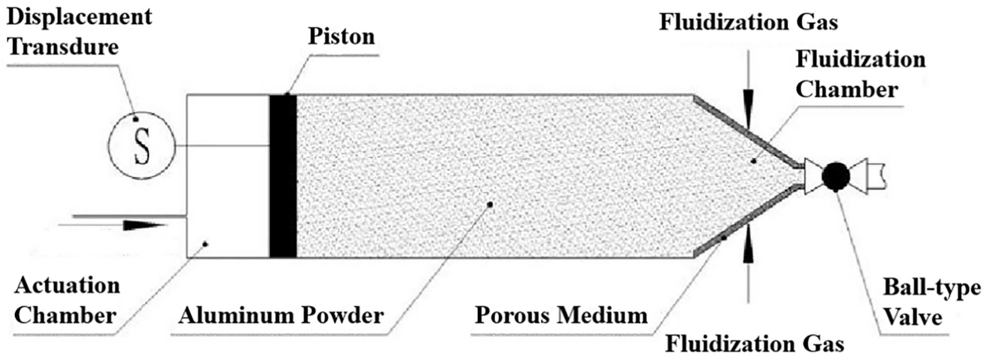


Fig. 12. Powder feed system of the pneumatic driven piston [15].

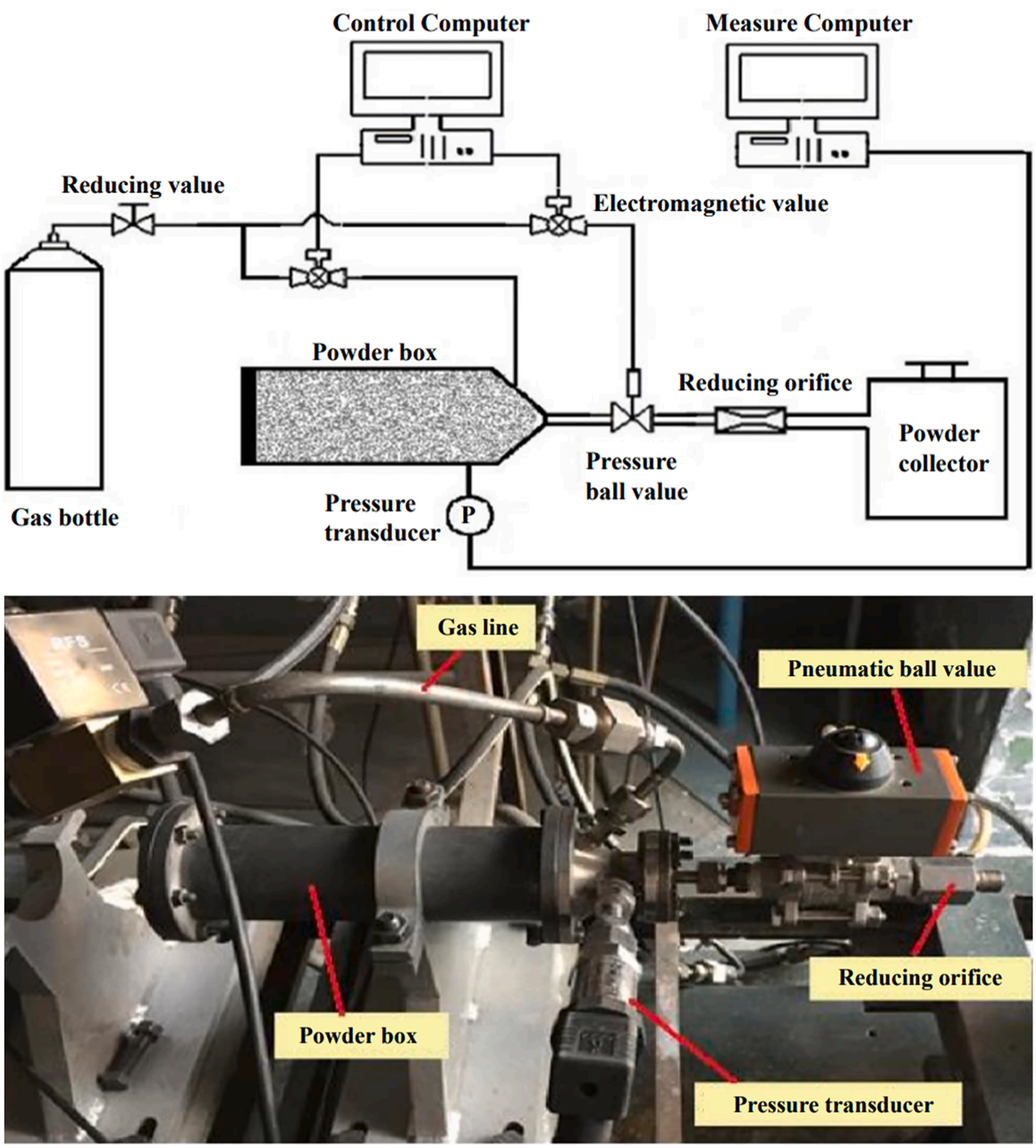


Fig. 13. Experimental system for particle mass flow rate measurement [48].

coupling characteristics with combustion oscillation under high pressure, as exhibited in Fig. 13. By calibrations of experiment and numerical calculation, a semi-empirical prediction model of powder mass flow rate at the starting stage of the powder feed system is established, the characteristics of a particle starting at high pressure are numerically analyzed, and two kinds of powder mass flow rate regulation methods are proposed.

In summary, the development of powder feeding systems has experienced a change from motor driven piston to the pneumatic driven piston. The powder feed system of motor driven piston has obvious advantages for piston motion stability regulation, but the system puts forward high requirements for motor power. Especially when the pressure in the storage tank is high, it is difficult for the motor to push the piston and thus the piston motion speed is difficult to regulate if an equal pressure balance is not taken. At the same time, since the piston is directly connected to the motor rod, it will increase the length of the powder feed system accordingly, which is not beneficial to system integration.

Although the powder feed system of the pneumatic drive piston is more complex in terms of gas circuit design, it can achieve piston speed regulation by adjusting the amount of driving gas and fluidizing gas. The driving gas and fluidizing gas can share a common gas source, without the need for an additional piston drive device. When the pressure difference between the drive chamber and the fluidization chamber is greater than the combined resistance, the piston could be motivated. Moreover, the piston guide rod can be removed in this way, and the system is more integrated. It can be seen that the powder feeding system of the pneumatic drive piston is more suitable for powder fueled ramjets, and further research needs to focus on the accurate regulation of the pressure of fluidized gas and drive gas.

3.2. Ignition and combustion processes of powder fuel

The combustion process of metal particles is typically solid particle combustion, which is quite different from the combustion process of carbon, boron, and other particles with high melting points. The melting point of metal particles is also lower than the flame temperature. In the combustion process of metal particles, the melting phenomenon first occurs, followed by the diffusion of metal vapor from the metal surface to the environment. Subsequently, the diffusion flame forms due to the combustion reaction near the surface of the particle with the oxidizing gas in the surrounding medium. However, during the combustion of metal particles, a large quantity of finely condensed metal oxides is produced, and a large amount of reaction heat is released, while the condensed phase combustion products diffuse to both the particle/droplet surface and the environment. Due to the low temperature of the particle surface, condensed phase combustion products permeate into the metal surface where the condensed phase deposition occurs, and metal oxide caps are generated.

3.2.1. Magnesium

The research work on the combustion properties of magnesium began in the 1950s, which focused on the experimental study of the ignition and combustion process for magnesium particles. Since the 1990s, with the continuous improvement of the basic theory and the level of experimental technology, the research on the experimental, theoretical and computational models of the ignition and combustion of magnesium particles has been developed significantly.

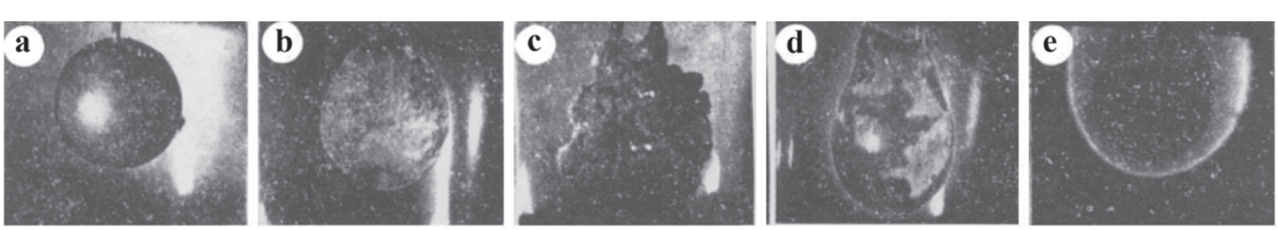
In 1959, Cassel and Liebman [51] studied the ignition characteristics of magnesium particles and particle clusters and found that the ignition temperature of single particles was inversely proportional to the particle size, while the ignition temperature of larger concentration particles was lower than that of small particles. The ignition temperature of particle clusters is generally lower than that of single particles, and it is pointed out that this is due to the cooperative effect between particles.

Derevyaga et al. [52] researched the combustion mechanism of magnesium particles in high-temperature O_2, using high-temperature oxidizing gas to heat the particles until combustion. The whole combustion process is shown in Fig. 14. Fig. 14(a) is the initial state of particles. When the particles reach thermal equilibrium, the surface is covered with an oxide layer (Fig. 14(b)). With the increase in temperature, the particles expand and the surface begins to appear with granular lumps (Fig. 14(c)). The expansion of the particles results in the rupture of the oxide layer on the surface and the exposure of liquid magnesium. The particles catch fire (Fig. 14(d)) and quickly convert to a gas-phase combustion state (Fig. 14(e)). The combustion residue is porous and significantly larger than the initial particle size. Huang et al. [53] also observed a similar combustion process, as shown in Fig. 15.

Based on the radiometric spectral intensity analysis and synchrotron photography, Takeno et al. [54] carried out experimental research on the ignition combustion process of magnesium and magnesium–aluminum alloy in high-temperature airflow and pointed out that the oxidative combustion process of pure magnesium undergoes four stages respectively. The first stage is that the metal surface generated a thin layer of black material, and the whole surface is continuously protective, and the main components are magnesium oxide and carbon. In the second stage, the black protective layer is ruptured, the oxidation is accelerated, and a porous white deposit layer appears. The third stage is about the explosion of the magnesium surface when the temperature reaches about 900 K. The fourth stage discusses that when the protective layer is completely ruptured, magnesium vapor and the oxidant react violently and enter into the combustion stage while defining the three characteristic temperatures of critical temperature, transition temperature, and ignition temperature.

Dreyer et al. [55] utilized laser-induced fluorescence technology for the first time to evaluate the distribution of MgO produced by magnesium combustion in CO_2 and O_2. In the reaction test of magnesium with 21% O_2, the fluorescence of MgO appeared far away from the surface of molten magnesium particles, and the closer to the surface of the particles, the weaker the fluorescence intensity, indicating that the generation of MgO occurred in the gas phase chemical reaction. In the experiment, it was observed that the reaction of magnesium and CO_2 was mainly gas-phase combustion, but there would be a pulsation phenomenon.

Goldshleger et al. [56] investigated the oxidation and combustion properties of individual magnesium particles in an oxygen/argon mixture. The temperature of the particle surface under different oxidants and temperatures and the temperature of gas-phase close to the sample surface was measured, and the high-temperature oxidation diagram of magnesium was obtained. The reaction of magnesium in the mixture of oxygen and argon can be divided into five modes: the magnesium mainly oxidizes slowly at a lower temperature (Zone I). When the temperature rises, it develops from slow oxidation to unstable multiphase combustion (Zone II). When the temperature continues to go up or the oxygen concentration increases, multiphase combustion and gas phase combustion exist simultaneously (Zone III). The temperature



(a) initial particle (b) melting (c) expansion (d) ignition (e) gas-phase combustion

Fig. 14. The changes of magnesium particles with a diameter of 6 mm surface with time [52].

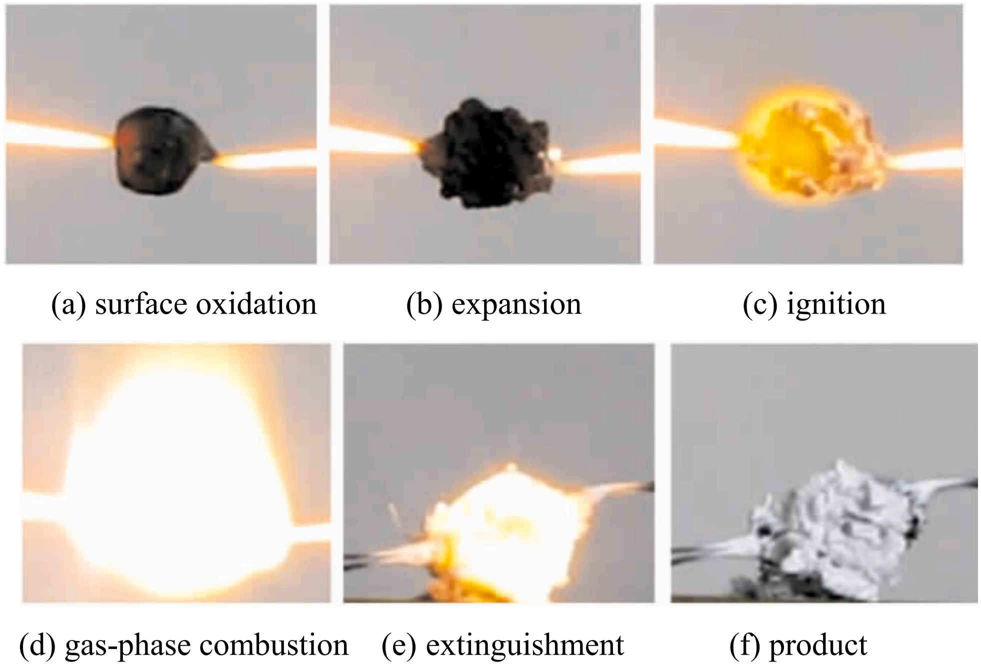


Fig. 15. Combustion process of a magnesium particle in the air [53].

continues to rise, and if the oxygen concentration is low, it develops into oscillatory combustion (Zone IV). If the oxygen concentration is high enough, gas-phase combustion (zone V) progresses, leaving a porous thin layer of magnesium oxide.

Brzustowski et al. [57] described the combustion process of magnesium particles in O_2 as follows: A, B, and C are particle surface, flame surface, and infinity respectively; magnesium vapor diffusion zone is between AB; oxidizer diffusion zone is between BC, as shown in Fig. 16. Assuming that the combustion is quasi-steady, magnesium vapor and O_2 react by diffusing to the flame surface in an equivalent ratio. The heat released by the combustion maintains the evaporation of particles and brings the reaction zone to flame temperature. Aiming to describe the various phenomena that appeared in the process of particle ignition more accurately, Rozenband et al. [58] developed a single magnesium particle ignition model in which the oxide layer on the particle surface was segmented into an internal protective oxide layer and external non-protective oxide layer.

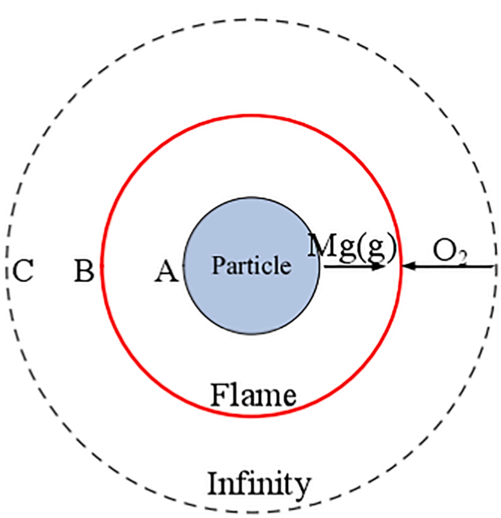


Fig. 16. Schematic of the diffusion flame model [57].

Based on the above analysis, lots of achievements have been made in the ignition and combustion of magnesium in the O_2 atmosphere, and the research on the ignition and combustion of magnesium in the CO_2 and H_2O atmosphere is also gradually rising. Nevertheless, the mechanism of ignition and combustion of magnesium is not fully comprehended. It is generally believed that magnesium is a surface reaction before ignition, magnesium oxide film has no protective effect on magnesium, and magnesium combustion is gas-phase combustion. Magnesium oxide will accumulate on the surface before ignition, accompanied by bubbling and blackening of the surface. When the temperature of magnesium reaches near the melting point, the surface reaction is rapidly intensified and the combustion stage is soon carried out. The combustion mechanism of magnesium in different oxidizing atmospheres is slightly distinct. However, different scholars hold distinct views on the division of different stages in the magnesium ignition and combustion process, the definition of the turning point of magnesium ignition to combustion, and the control factors affecting magnesium ignition and combustion.

The ignition model of magnesium particles in different oxidizing atmospheres mainly considers the stress of the oxide layer on metal particles and the multiphase chemical reaction on the surface. Some details in the particle ignition process have not been considered in existing models, such as the flashover and extinction of the local ignition. At present, the combustion model of magnesium particles develops from the traditional droplet combustion model, which can reflect part of the physical properties of the combustion process to a certain extent. However, a large number of assumptions are applied in the establishment of each model, which often rarely involves the details of combustion reactions, and there are still certain gaps in the accurate description of the particle combustion process. To better perfect the ignition and combustion model of magnesium particles, it is necessary to have a deep understanding of the ignition and combustion process of particles and master the formation mechanism of the surface oxide layer as well as its influence on heat and mass transfer in the combustion process.

3.2.2. *Aluminum*

Since the 1950s, the application of aluminum particles as a high-energy metal additive in solid propulsion systems has contributed to a boom in the study of its ignition and combustion properties. However, the major difference between magnesium particles with aluminum particles is that it is difficult for aluminum particles to start burning in oxygen because of the dense oxide film on their surface, which prevents them from reacting with oxygen.

In 1959, Brzustowski et al. [59] first pointed out the existence of evaporation mode combustion behavior of aluminum in air. The flame temperature of aluminum is 4000 K, which is higher than its boiling point of 2791 K. The temperature of the high-temperature flame is returned to the surface of aluminum particles, which causes the aluminum to react with the oxidant and evaporate as a gas phase. In order to study the combustion law of a single aluminum particle, Bucher et al. [60] designed an experimental device for the free-dropping combustion of aluminum droplets as shown in Fig. 17. After the aluminum strip enters the combustion chamber, it melts into aluminum droplets under the heating of a CO_2 laser and is ignited. The supply speed of the aluminum strip is under control to guarantee the size of aluminum droplets. The whole combustion process in a photograph, as shown in Fig. 17, particle time, and the location of one-to-one correspondence, can judge the aluminum particles in the combustion status of each moment. The quenching plate is installed below the droplet drop, and the mass size and flame radius of aluminum particles at different times could be obtained by changing the height of the quenching plate. The burning rates of aluminum particles with diameters of 100–215 μm in air, N_2O, CO_2, CO, and H_2O are obtained, and the ratio of flame radius to the particle radius is measured.

After the 1990s, with the continuous improvement of advanced optical measurement methods, the diagnostic measurement methods of aluminum particle combustion become more and more varied. Becktead et al. [61] built an experimental system to explore the influence of gas-phase component diffusion on the burning rate of aluminum particles, in which the relationship between burning rate and diffusion distance, as well as diffusion and gas components, was explored. Quenching disks were used to capture aluminum particles in combustion. The presence of an Al_2O_3 cap was observed by SEM, displayed in Fig. 18.

Soo and Julien [62,63] injected aluminum powder with an average diameter of 5.6 μm into a Bunsen burner flame premix with methane as well as air and studied the combustion temperature and combustion rate of the flame at different concentrations of aluminum powder. In the experiment, a spectrometer with a resolution of 1.5 nm was used to collect the spectral distribution of the combustion flame between 350 nm and 1000 nm, and the temperature of the condensed phase products in the flame was obtained based on Planck law. Subsequently, Soo et al. [64] also investigated the combustion characteristics of aluminum particles with an average particle size of 4.2 μm in air and methane/air offset combustion flame. The emission imaging spectrometer,

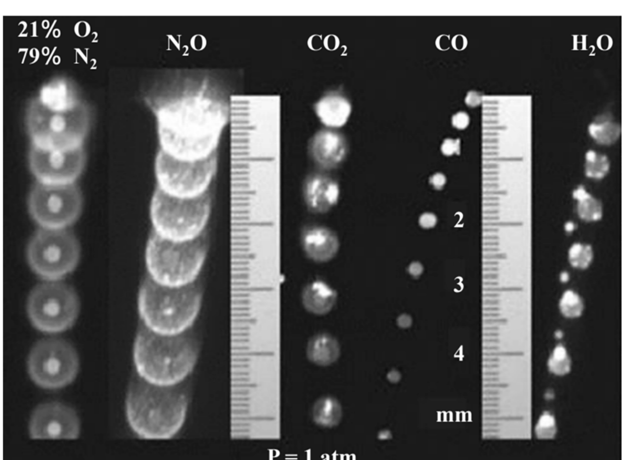


Fig. 17. Flame structure of the single-particle Al combustion experiment [60].

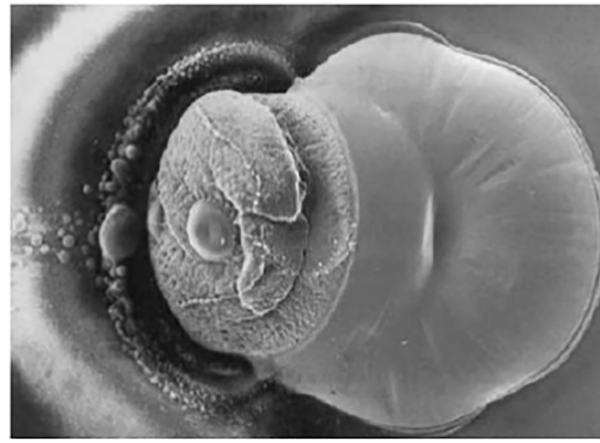


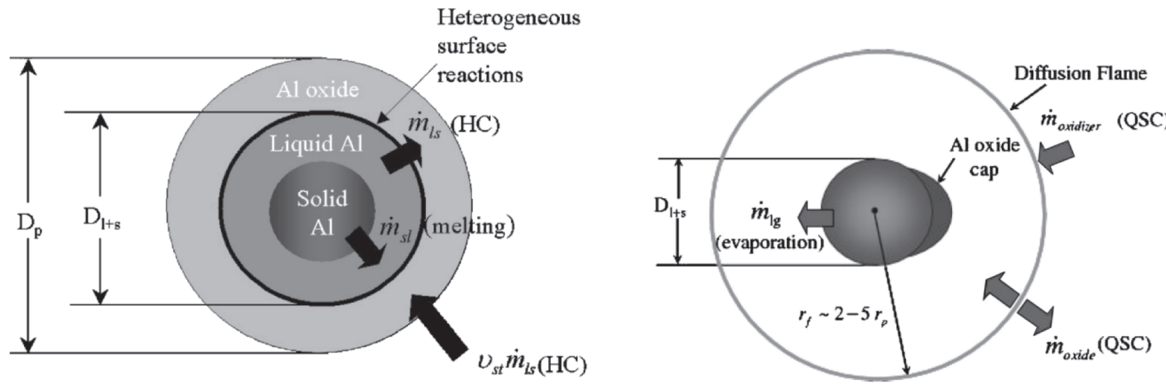
Fig. 18. Aluminum particle quenched [61].

absorption spectrometer, and other experimental devices were applied to observe the combustion process of aluminum particles, so as to obtain the combustion mechanism of particles and the characteristic combustion time of particles. It is found that when aluminum particles are burned in the air, there is a small gas diffusion flame around the individual aluminum particle. However, in the combustion flame of Al particles/methane/air, no small gas diffusion flame is discovered around the Al particles, which proves that the combustion process is a surface chemical reaction controlled by chemical kinetics.

Through the establishment of an aluminum particle ignition combustion model, more abundant parameters can be obtained in the process. Although aluminum is a light metal, its burning process could not directly utilize the droplet evaporation combustion model to describe, mainly because the aluminum gas-phase combustion products will condense into liquid or solid phase, and deposition on the particle surface oxide caps. The oxidation cap can adjust the evaporation rate and temperature distribution of aluminum particles and lead to aluminum vapor ejection.

DesJardin et al. [65] comprehensively pondered the ignition and combustion process of aluminum particles and the deposition process of oxidation products, and then proposed a unified ignition and combustion model, as shown in Fig. 19. In the ignition stage, aluminum particle melting and surface multiphase reactions are the main physical and chemical processes. In the combustion stage, the aluminum particles are subjected to quasi-steady diffusion combustion, and the deposition of oxides on the surface of the particles is considered. In the combustion process of aluminum particles, the condensation products will form oxidation caps on the leeward side of the particles, which will cut down the chemical reaction area on the surface of the particles and cause the particles to explode violently.

Yang et al. [66] believe that the ignition and combustion process of the aluminum particles is the same as that of conventional hydrocarbon droplets, except for the role of the oxide layer on the surface of the aluminum particles. The ignition and combustion process of aluminum particles includes heating, ignition, and quasi-steady-state combustion, and the effect of the oxide layer runs through the whole process. In view of the oxidation layer in the initial state of aluminum particles and the mechanism of the oxidation cap during combustion, they proposed an ignition combustion model in a static atmosphere. Before ignition and aluminum particles are coated with a layer of oxide, for aluminum particles with a diameter of several hundred microns, the melting of oxide is critical. In the ignition stage, the particle energy balance equation is established by observing the processes of convective heat transfer, thermal radiation, melting heat absorption, and heat release by surface multiphase chemical reaction, and it is considered that the ignition stage ends when the temperature of aluminum particles reaches the melting point of aluminum oxide. In the combustion stage, based on



(a) Multi-phase chemical reaction in ignition stage (b) Thin flame surface model in combustion stage

Fig. 19. Ignition and combustion models of aluminum particles [65].

the compositional conservation equation and energy conservation equation, the quasi-steady state combustion model is established by introducing the central symmetry hypothesis and the thin flame surface hypothesis. Owing to the surface tension of alumina, oxidation caps are formed on the surface of liquid aluminum, which will lessen the effective area of surface chemical reaction, and violent gas injection and asymmetric combustion will occur with the formation of the oxidation cap.

King et al. [67] proposed a particle combustion model that indicated the change of aluminum particle diameter and oxidation cap shape with time. The particle surface, flame surface, and product condensation area are used to distribute the space around aluminum particles into three areas, as shown in Fig. 20. The condensation reaction of oxides is mainly on the surface of aluminum particles, while the flame surface is the reaction of aluminum vapor and oxidizing gas to produce oxides. "Oxidation smoke" lies in the product condensation area, which is the chemical reaction of oxides. In the model, it is assumed that the volume and shape of the oxidation cap on the surface of aluminum particles change constantly during the combustion process, but at the interface between the above two, it is approximated that the section of the oxidation cap is always perpendicular to the surface of aluminum droplets. Because the model is described by the algebraic equation, the calculation amount can be greatly reduced, and it is suitable to be used as a submodule of the solid propellant combustion model.

Feng et al. [68,69] systematically carried out the experimental research on the ignition and combustion process of single micron aluminum particles in a high-temperature gas environment, established the ignition and combustion test system and test method of single micron metal particles, and analyzed the change rule of ignition delay time and combustion time of aluminum particles, initial particle size, environmental oxygen content, environmental temperature and other factors in detail. Meanwhile, based on experimental research, Feng et al. [70] established the ignition model and combustion model respectively considering the mechanism of the oxidation layer/oxidation cap on the surface of aluminum particles. They also conducted numerical simulation research on the ignition and combustion process of aluminum particles in typical working conditions.

A large number of experimental studies have been carried out on the ignition and combustion process of a single aluminum particle. Through precise experimental design, combined with the laser, spectral and high-speed photography, the ignition and combustion process of a single

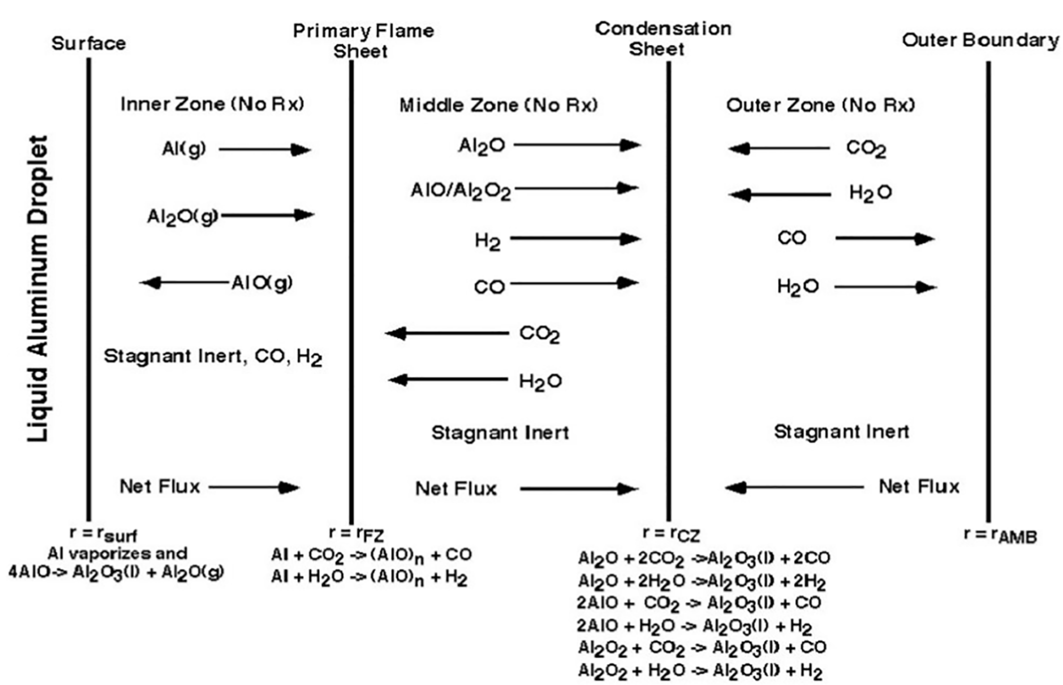


Fig. 20. Sketch of the aluminum combustion model [67].

aluminum particle can be completely recorded. In the existing experiments, aluminum particles are usually ignited and burned in a single oxidizing atmosphere, while the combustion process of aluminum in the solid propulsion device is completed in a high-temperature gas environment composed of a variety of oxidizing gas. Therefore, it is necessary to further study the ignition and combustion process of aluminum particles in high-temperature mixed oxidizing gas. At the same time, the ignition and combustion characteristic parameters of aluminum particles are closely related to the initial diameter and shape of the particles, hence the next step needs to further improve the characterization of the initial parameters of aluminum particles.

Since the 1960s, the research on the ignition and combustion model of aluminum particles pay more attention to the mechanism of the initial oxide layer on the surface, the suboxide, and the oxidation cap in the ignition and combustion process of aluminum particles. However, the research on the ignition and combustion mechanism of aluminum particles and the details of the ignition and combustion process is still not in-depth. For purpose of meeting the needs of the ignition and combustion sub-model of aluminum particles for the internal numerical simulation of the solid propellant device, it is essential to perfect the oxidation layer change history and oxidation cap dynamic movement model of aluminum particles in high temperature mixed oxidizing gas environment.

3.3. Combustion organization technology

Because of the extremely high velocity of the incoming flow and the size limitation of the combustion chamber, the residence time of fuel and airflow is very short [71]. Therefore, it is extremely difficult to complete the efficient mixing and ignition, so as to achieve stable combustion of the propellant. Specifically, the solid phase has a much higher density and momentum than the gas, and its transport process and mixing effect are different from that of the gas or liquid phase. When the volume fraction of the particle phase in the combustion chamber is large, it is also necessary to consider the interaction between the particles. The presence of complex shock wave structures in the combustion chamber would further affect the mixing of the powder fuel as well [72]. In terms of powder fueled ramjets, the fuel enters the combustion chamber in the form of gas–solid two-phase jet flow, which thus undergoes evaporation, oxide film rupture, surface heterogeneous reaction, gas-phase reaction, and product condensation process. This also leads to the specificity of the mixing process and the difficulty of the combustion organization. In order to achieve adequate mixing and combustion of powder propellant, the current development of research is mainly concentrated on two aspects of powder injection and combustion organization.

Fluidized powder particles have certain quasi-fluid properties, but their rheological properties are far inferior to those of liquid fuel. The gas–solid flow separation often occurs in the sophisticated powder injection structure, resulting in local deposition of powder propellant, and then greatly affects the stability and safety of powder fueled ramjets. By optimizing the design of the powder fuel injector, it can achieve better injection and dispersion effects in a larger powder fuel mass flow rate regulation ratio. Under current technical conditions, the structure of powder injector generally abandons the configuration of liquid collecting cavity and multi-point array injection, and adopts single-point injection or ring injection with a simpler structure and smoother flow, so as to attain the effect of continuous injection of powder propellant.

The powder injector configuration designed by Bell Aerospace [42] is shown in Fig. 21. Fig. 21(a) demonstrates the premixed powder injection mode. The powder fuel and oxidizer enter the premixing structure from the central and lateral ducts respectively and are then injected into the combustion chamber after mixing. The pressure in the combustion chamber is oscillating during the operation of this injection mode. Fig. 21(b) displays the non-premixed powder injection mode, in which the powder oxidizer enters the central inlet in a swirl flow mode, and the powder fuel gets into the injector laterally and comes into the combustion chamber with a ring injection mode. This injection mode has good safety, and the use of combustible fluidized gas significantly enhances the working stability of the engine.

In the Al/AP powder rocket engine ignition experiment carried out by Northwestern Polytechnical University in China [73], a non-premixed injection of powder propellant is adopted, as shown in Fig. 22. The central annular channel is the oxidizer channel, which is injected into the combustion chamber with a half-angle of 17°, and the outer annular channel is the powder fuel channel, which is transfused into the combustion chamber in the form of a swirl. The injector has good injection performance and flame stability. It can be seen from the current research status of powder injectors that non-premixed mode is the main choice of powder injection. Powder injection velocity is mainly 14–42 m/s, and powder fuel transport speed is related to the flow velocity condition of suspension flow. At the same time, the pressure drop of the injector differs greatly, which is mainly related to the configuration of powder injection gas and the difference in fluidization gas.

Focusing on the powder fuel injection characteristics of the powder

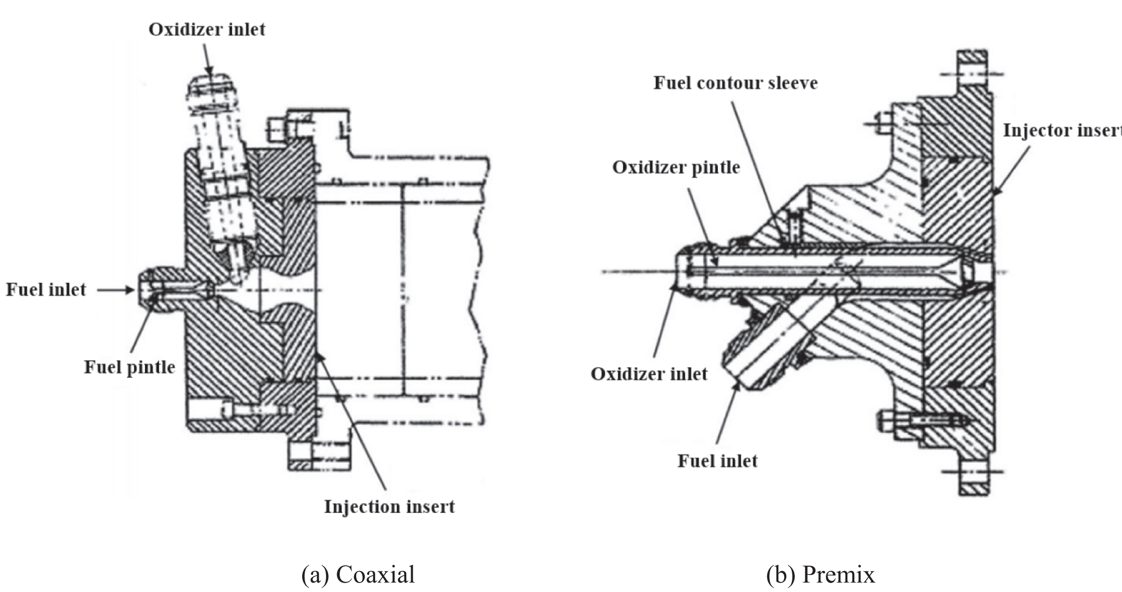


Fig. 21. Powder injection of Bell Aerospace [42].

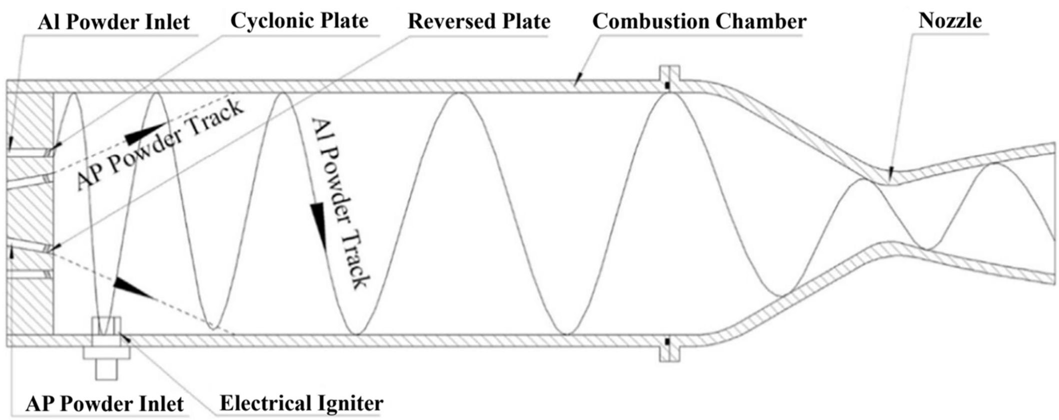


Fig. 22. Powder injection of Northwestern Polytechnical University [73].

fueled scramjet, Ding et al. [18] investigated the gas–solid flow in the nozzle and the effect of convergence angles on the flow field by the coupled model of computational fluid dynamics-discrete element method. The results present that the addition of the powder is able to produce a large perturbation of the gas phase flow field. As the nozzle convergence angle increases, the particle collision frequency has increased, and the expansion angle of the gas–solid jet at the exit has increased, which can be seen in Fig. 23. This investigation provides a reference for the injection mechanism of the powder fuel gas–solid flow and the design of a powder feeding system.

For the powder fueled ramjet, the combustion chamber should not only ensure the smooth ignition of powder fuel but also needs to form a stable flame, to maintain a stable combustion process. Combustion of powder fueled ramjets is in high-speed airflow, the flame stabilization methods commonly used are blunt flame stabilization, swirl combustion stabilization, jet combustion stabilization with large velocity difference, burst flame stabilization, and cavity flame stabilization [74]. Blunt body flame stabilization is in the extensive use of pulverized coal burners and aero engines, whose principle is to form a stable backflow zone and thus plays a good flame stabilization role. Swirl combustion stabilization makes use of strong rotating airflow to produce a strong high-temperature backflow zone, so as to strengthen the ignition and combustion of fuel, but also accelerate the mixture of fuel and gas. The combustion stabilization technology of a large velocity difference jet is a strong turbulent flow field produced by the combination of a high-speed jet that is based on the direct current jet. In recent years, with the development of scramjet, the cavity flame stabilizer which integrates fuel injection, mixing, and flame stabilization is the most promising one among several new concept flame stabilizers which can advance the performance of scramjet and obtain higher net thrust [4,75].

Kong et al. [33] devised a trapped vortex flame holder for the powder fueled ramjet, in which the configuration of the trapped vortex flame holder-based powdered fuel ramjet was put forward. The numerical simulation method was used to simulate the three-dimensional flow

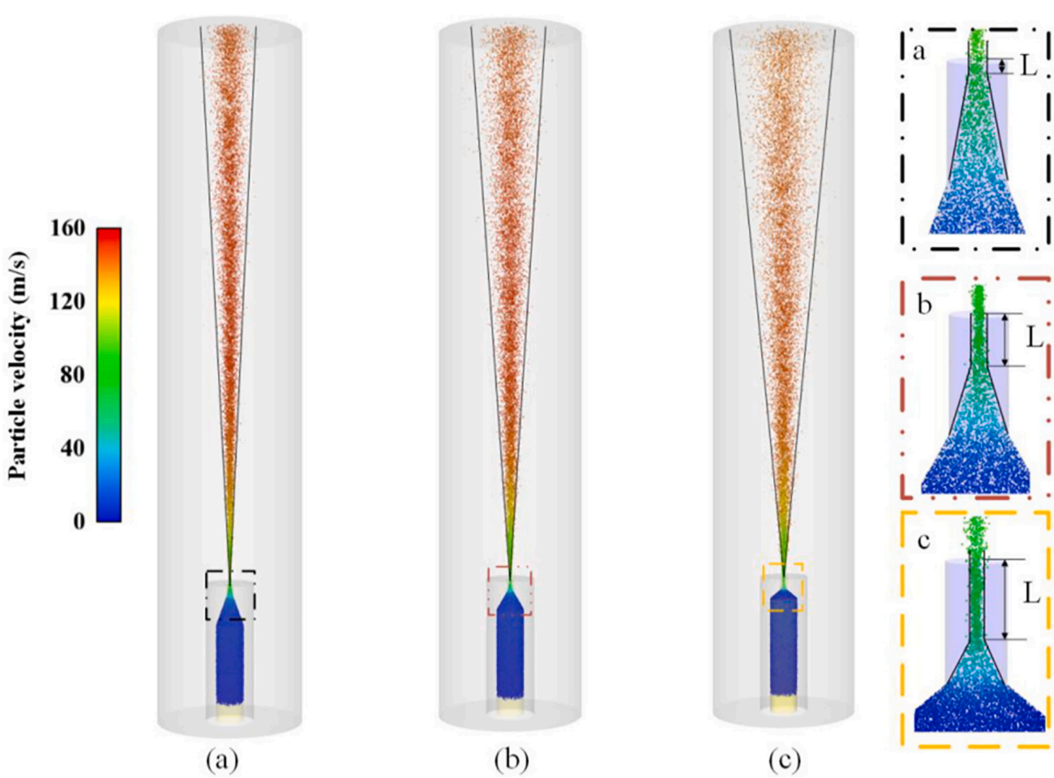


Fig. 23. The particle velocity distribution of different convergence angles. (a) φ = 20°, (b) φ = 30°, and (c) φ = 40° [18].

field of the magnesium-based powder fueled ramjet, and the effect of the flow field structure on the combustion efficiency before and after the improvement was compared and analyzed. The results show that the ramjet combustion efficiency is improved by 10% with the application of a trapped vortex flame holder. Xi et al. [76] proposed three head shapes and three exhaust inlet types of the powder fueled ramjet combustor to improve the mixing efficiency. The inlet species of the combustion chamber are water vapor and carbon dioxide, and the mole fraction (CO_2) distribution on the x-z central sections of the combustion chamber is presented in Fig. 24. The cylindrical head forms a recirculation zone at the head of the combustion chamber, which leads to powder concentration in this area. On the contrary, the structure of the round head and the coned head weakens the recirculation inside the head region, so the exhaust gas from the fuel gas generator facilitates the powder mixing process. When the exhaust gas inlet of the inclined six-hole type is adopted, it enhances the powder fuel mixing effect due to the strong flow impingement in the core of the combustion chamber.

At present, a large number of investigations have been done on the mixing enhancement and combustion organization of gas and liquid fuel in the scramjet [77,78]. There is limited research available to study the combustion organization technology of powder fueled ramjets alone, where the basic scientific issues involved are gas–solid two-phase mixing and combustion. Analogously, the combustor of a solid rocket scramjet contains solid particles combustion, and related investigations can be exploited to guide powder fueled ramjet design [79,80]. Li et al. [81,82] investigated the combustion of two phases in the combustor of a solid rocket scramjet. It was found that the combustion efficiency depends mainly on the combustion of the particle phase. There is a competitive relationship between the particle phase and the gas phase in the combustion process, and the high temperature derived from the gas phase combustion can promote the particle phase combustion. Gao et al. [83] conducted a numerical study of the mixing and heat release characteristics of a solid fuel scramjet combustor. The changes in lobe sweep angle and height have a significant influence on the combustion efficiency, gas mixing degree, and oxygen-fuel ratio. In order to improve the combustion efficiency of boron-based solid rocket scramjet, Liu et al. [84] proposed a hybrid enhancement and combustion organization scheme, which is based on the combination of the cavity and aerodynamic ramp. The results indicated that the parameters of the jet had a much greater effect on the combustion efficiency and total pressure recovery than the length-to-depth ratio of the cavity. Cavity and aerodynamic ramp can strengthen the particle reflux, thus improving the mixing and combustion efficiency.

3.4. Multiple-start and thrust regulation

Because of the specificity of the powder fuel flow pattern, powder fueled ramjets theoretically exhibit superior multiple ignition start and thrust regulation capability. Currently, more research on this aspect is performed in powder rocket motors, which can provide a reference for the multiple starts and thrust regulation technology of powder fueled ramjets.

Li et al. [73] conducted an experimental study on the multi-pulse function of the ammonium perchlorate/aluminum powder rocket motor. Four consecutive engine starts at short intervals and three engine starts at long intervals were achieved, which is presented in Fig. 25. The test results revealed that the engine multi-pulse start has good repeatability, and the combustion chamber pressure oscillation amplitude can be effectively reduced by increasing the engine operating pressure.

The thrust regulation process is complex, involving more components, so it is more difficult to carry out powder engine thrust regulation experiments. Zhang et al. [85] employed a high-energy spark plug as the ignition source and successfully achieved multiple ignitions start of the powder rocket engine. Meanwhile, powder fuel was able to self-sustain stable combustion, with a combustion efficiency of over 80%. By reasonably adjusting the mass flow rate of powder fuel and oxidizer, the thrust adjustment function of the powder rocket motor is successfully realized, and the thrust adjustment ratio reaches 6.5. Wu et al. [86] investigated the effects of propellant mass flow rate and combustion chamber operating pressure on thrust regulation, as shown in Fig. 26. The powder supply performance, combustion efficiency of the engine, and pressure oscillation were further analyzed. During the variable flow rate regulation, it was found that the AP powder responded promptly and transported smoothly, while the Al powder stalled and brought instability to the powder transport. Overall, the thrust regulation ratio of powder rocket motor reached 1:2.94, which can meet the demand for thrust regulation.

From the engineering application point of view, although the above experimental studies were conducted on powder rocket motors, it has been confirmed to a certain extent that powder engines have good multiple starts and thrust regulation capability. Compared to powder rocket engines, powder fueled ramjets operate in a more sophisticated environment, such as the incoming flow conditions change drastically, flight overload impacts powder fuel delivery stability, and coupling

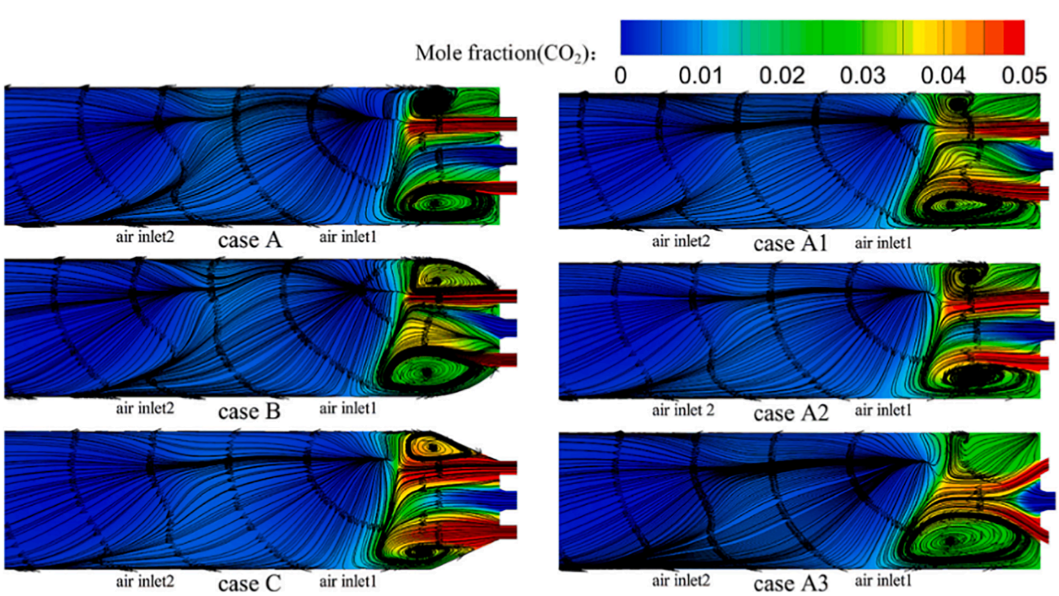


Fig. 24. Mole fraction (CO_2) distribution on the x-z central sections of the combustion chamber [76].

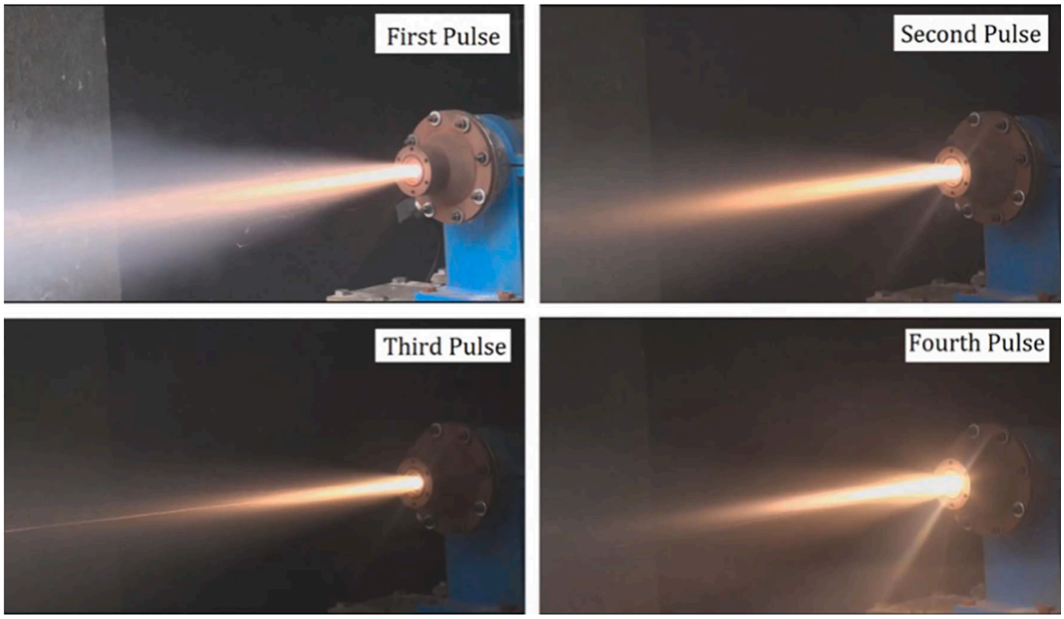


Fig. 25. Multi-pulse test of the powder rocket motor [73].

(a) Small thrust stage (b) Large thrust stage

Fig. 26. Thrust regulation test of the powder rocket motor [86].

interaction between fluidization and combustion. Furthermore, a closed-loop control system is required to regulate the powder fuel mass flow rate in response to the variation in flight conditions and thus match the performance of the power system. Nevertheless, these sections of the research have not been performed yet.

3.5. Thermal protection technology

The hypersonic vehicle powered by the powder fueled ramjet has been in power flight for a long time, and its working time is much longer than that of the traditional solid fueled engine. Additionally, the combustion environment of the powder fuel is extremely harsh, where the combustion temperature is above 3500 K and the mass fraction of the condensed phase product exceeds 40%, exposed to extremely high heat flow density and poor condensed phase deposition environment. The combustion form of metal powder differs from that of conventional fuel. The combustion products often have high melting and boiling points, and the solidified particles will collide with the wall, aggravating the ablative and destruction of the engine wall. Under the action of the flow field, combustion products will also bond to the wall of the combustion chamber, nozzle, and other parts to form a sedimentary layer, which will gradually increase in size over time, thus affecting the performance of the engine. Besides, powder fuel is of a high calorific value, and the combustion of powder fuel causes a constant increase in the temperature of the combustion chamber walls, which affects the yield strength and ultimate strength of the material at high temperatures. If the yield strength is exceeded, the engine will be permanently deformed, which limits the engine from operating for long periods of time. Consequently, strict thermal protection design is of great necessity.

There are two main types of thermal protection for power devices: passive schemes and active schemes. The passive scheme is to utilize lightweight ablation-resistant materials or new high-temperature-resistant materials for thermal protection of the engine. The active cooling scheme takes the fuel as the coolant and takes away the heat through the flow of coolant to cool the engine, mainly including gas film cooling, sweating cooling, and regenerative cooling, among which regenerative cooling is considered as one of the best thermal protection schemes for scramjet. Luo et al. [87] reviewed the scramjet development of regenerative cooling, introduced the superiority of regenerative cooling in scramjets, and summarized the necessity of regenerative cooling progress of supercritical fluid heating in detail hydrocarbon fuel coking. Then the heat transfer enhancement structure inside the regenerative cooling channels was discussed. It is considered that the lattice structure and multifaceted nanostructure are important development directions in the future.

Most of the experiments on powder fueled ramjets are based on passive thermal protection schemes, and no further research work has been carried out in accordance with the actual flight environment. Since the thermal environment faced by powder fueled ramjets are extremely distinctive, it is not possible to directly apply the thermal protection schemes of traditional solid ramjets and liquid ramjets. Hence, it is necessary to explore composite thermal protection or new thermal protection solutions. Nowadays, regenerative cooling with supercritical fluids is perhaps one of the most promising thermal protection schemes [88,89].

Based on the operating characteristics of powder fueled ramjets, we propose a prospective and feasible thermal protection scheme. On the one hand, the multi-functional reuse of carbon dioxide is fully utilized in powder fueled ramjets. The supercritical CO_2 Brayton cycle has received a lot of attention for its superior performance and has become a frontier research hotspot in the field of thermal power utilization [90–92]. Miao et al. [88,93] demonstrated that the ramjet thermal management system based on the supercritical CO_2 Brayton cycle can reduce coolant (fuel) consumption by nearly 30 percent compared to conventional cooling systems, while significantly increasing output power. Accordingly, carbon dioxide can be adopted as a cooling medium and fluidization gas in the engine system. In the actual working process, the CO_2 in the high-pressure storage tank is depressurized by the pressure reducer and first flows through the regenerative cooling channel in the combustion chamber to cool the wall surface. Then it enters the powder fuel storage tank to pressurize and fluidize the powder fuel. Eventually, the CO_2 carries the powder fuel into the combustion chamber and participates in part of the chemical reactions.

On the other hand, the lattice structure has great advantages in heat dissipation, specific strength, energy absorption, and vibration damping [94,95], making it the main structure for the cooling channels of the combustion chamber. Yun et al. [96] proposed a face-centered cubic with vertical struts lattice channel (FCCZ), as shown in Fig. 27. They estimated the heat transfer and stress characteristics of FCCZ by a thermal fluid–structure interaction one-way coupled model. The results demonstrated that FCCZ has high heat transfer performance and structural stability, which is recommended to promote its application. Yuan et al. [97] reviewed the research on lattice sandwich active cooling structures, focusing on the current status of investigations on their preparation process and heat transfer characteristics. Study results indicated that the cooling effect of lattice structure is significantly better than the rectangular channel structure, and its excellent designability can be used to design a cooling structure with high heat transfer, low-pressure loss, and lightweight. Of course, this thermal protection scheme and the thermal cycle process need to be further demonstrated and studied in the future in accordance with the characteristics of the thermal environment of powder fueled ramjets.

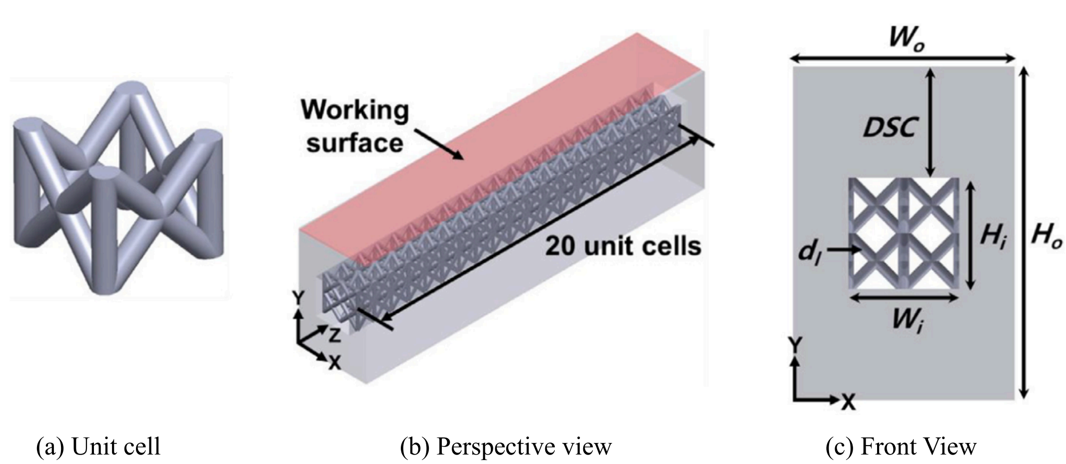
4. Conclusion and research recommendations

This paper has reviewed the research and development of powder fueled ramjets. The majority of the key technologies and development status have been described in detail. Based on the public literature above, the primary research and development trends of powder fueled ramjets have been summarized as follows.

(1) As a new concept power device, powder fueled ramjets have both the advantages of liquid fueled ramjets and solid rocket ramjets, which hold a broad application prospect in the hypersonic vehicle. For instance, the total temperature of the combustion chamber of a hypersonic vehicle can be as high as 4000 K at Mach = 8. Combustion products of powder fuel do not dissociate in this extreme environment and can meet the engine performance requirements.
(2) Powder fueled ramjets are in the proof-of-concept stage, the research is still in the preliminary feasibility demonstration of a single technology and the trial stage of technological breakthrough, and the maturity of basic theories and key technologies still needs to be improved, which easily leads to the dissociation of liquid fuel combustion products, thus reducing engine performance.
(3) In the development of powder fuel feed system, it has gone through the process from motor driven piston to pneumatic driven piston. From the comprehensive performance point of view, the powder feed system of pneumatic driven piston is more suitable for powder fueled ramjet.
(4) A large number of experimental and theoretical studies have been conducted on the ignition and combustion of powder fuel. Nevertheless, the mechanism of ignition and combustion is not yet studied deeply with further detailed scientific issues to be considered. The mixing enhancement of powder fuel plays an important role in the powder fueled ramjet, which involves gas–solid two-phase flow, and it generates a large impact on combustion.
(5) Research on thrust adjustment and work process control of powder fueled ramjets is in its infancy. Powder fueled ramjets are faced with a more severe thermal environment, and new thermal protection schemes need to be explored.

Above all, several recommendations for future research on powder fueled ramjets are proposed as follows.

(1) Improving powder fuel performance. It is of great significance to carry out powder loading process, powder modification research, improving powder particle loading efficiency, energy characteristics, transport characteristics, and chemical activity.
(2) Optimizing the powder feed process and injection mode. Through the development of powder conveying characteristics research, to realize the engine system multi-outlet supply capabilities.



(a) Unit cell (b) Perspective view (c) Front View

Fig. 27. Schematic of the face-centered cubic with vertical struts lattice channel [96].

Moreover, improving powder injection mixing effect and flow rate adjustment adaptability through multi-point injection spatial distribution characteristics study.

(3) Deepening the fundamental studies on the powder particle ignition and combustion mechanism that are involved in the powder fueled ramjet. The process of ignition and combustion of powder particles is extremely complex, so it is essential to further develop its mechanism and consider the influence of various factors on the process of ignition and combustion.
(4) Researching the efficient combustion organization technology and combustion stabilization. Powder-fueled ram engines also face the same challenges as scramjet, that is, mixing enhancement and flame stabilization. The fluidization, combustion, and coupling processes of the powder are also further considered. Besides, it is necessary to further investigate the fluidization, combustion, and coupling processes of the powder.
(5) Optimizing engine work process for fast response and precise regulation. The control feedback system can adopt a digital controller as the control center of the engine. By optimizing the control program and employing artificial intelligence technology, fast and intelligent control of the powder-fueled ramjet engine is further realized.
(6) Exploring new thermal protection schemes. The combustion environment of powder fuel is extremely harsh, and the high heat flux and bad coagulative deposition environment require higher safety and reliability of the combustor structure. Thermal protection of powder fueled ramjets is necessarily an active–passive composite scheme, and the regenerative cooling technologies based on lattice structure are probably a good way.
(7) Strengthening the research of numerical simulation. The flow and combustion processes inside powder fueled ramjets are concerned with the multiphase flow, dense particle flow, condensed phase particles, and complex phase changes, which are significantly complex. Correspondingly, the numerical simulation of powder fueled ramjets should be vigorously carried out in the future to improve and optimize the calculation model, which will further assist and guide the design and experimental research of powder fueled ramjets.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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