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Study on the Structure and Combustion Characteristics of Aerospace Engines

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Abstract. The propulsion performance and reliability of space engines are constrained by the degree of matching between structural design and combustion characteristics, yet systematic reviews of the coupling mechanisms between them are still lacking. This paper takes liquid rocket engines, solid rocket motors, hybrid rocket engines, and electric propulsion systems as the research objects. Employing a literature comparison and analysis method, it systematically examines the structural configurations, combustion characteristics, and the interrelations between them across these different engine types. The results reveal that injector geometry parameters determine combustion efficiency by governing the propellant atomization and mixing pathways; grain configuration and the burning rate pressure exponent jointly dictate the energy release characteristics of solid motors; the feedback loop between combustion chamber acoustic modes and heat release fluctuations constitutes the core mechanism triggering combustion instability; and the thermal design of regenerative cooling channels, together with the ablation behavior of throat materials, defines the constraint boundary of thermal–structural coupling. These findings offer a systematic perspective on the closed-loop logic of "structure supporting combustion, combustion verifying structure." Future work can employ multi-physics coupled numerical simulations to quantify these coupling relationships, thereby informing engine design optimization.

Keywords: Space propulsion engine, structural system, combustion characteristics, structure–combustion coupling

1. Introduction

Space propulsion engines are the driving force for launch vehicles and need to be driven forward in the development of space technology. To some extent, the schedule, cost and success of a mission are mainly determined by three factors of the engine: thrust level, fuel efficiency and operating stability. The light-off system for liquid oxygen/kerosene engines and electric thrusters of deep-space probes are all kinds of conversions of propellant energy into kinetic energy. The Structure of a space propulsion engine is responsible for bearing all the other parts and functions, and among them, the combustion properties determine how effectively and stably it can burn. Therefore, it is necessary to need to know how structural design variables affect combustion performance;

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otherwise, it will not be possible to improve the performance of today's engines or explore new paths for space propulsion.

Structurally, the technology system of space propulsion engines has been developing in many directions and includes liquid, solid, hybrid and electric propulsion. A typical structure of a liquid-propellant rocket engine is a thrust chamber, a turbopump feed system and valve and piping assembly, and it has a high specific impulse and is throttleable. Generally speaking, a solid rocket motor is an integrated structure that combines propellant storage and a combustion chamber; therefore, it cannot be throttled in real time and must be set in advance according to the shape of the grain. Hybrid rocket engines are an intermediate form between solid and liquid propulsion systems, and thus have achieved a certain level of power and reliability. Hall thrusters and ion thrusters are types of electric propulsion that ionise and accelerate propellant with the help of electromagnetic structures. At present, many domestic and foreign scholars have been focusing on cutting-edge problems such as combustion characteristics, atomisation and mixing processes for liquid engines, high-frequency combustion instability in liquid engines, burn rate modulation and erosive burning in solid motors, ionization efficiency and plume divergence in electric propulsion systems, etc.

Therefore, this paper reviews the structure and combustion characteristics of the four representative engine types and analyses their coupling from the aspects of combustion organisation, energy release, stability and thermal protection.

The rest of this paper will be organised as follows. Chapter 2 is the structure of representative engine types, Chapter 3 is their combustion characteristics, Chapter 4 examines how structural modifications affect combustion, and finally, Chapter 5 presents the conclusion and future direction. The aim of this paper is to build a system of ideas that can explain how structure affects combustion characteristics and thus provide theoretical support for later research on aerospace engines.

2. Structure and architecture of space propulsion engines

Space propulsion engine structures have different forms in many places. Liquid rocket engines, solid rocket motors and other propulsion systems have different technologies; therefore, they also have different ways of providing propellant, ways of organising combustion and characteristics of thrust.

2.1. Liquid rocket engine structure

Liquid rocket engines are generally variable-thrust types that can be started several times and have a relatively high specific impulse. There are several sub-systems, and they are connected by fluid lines and a control system.

The thrust chamber is the main part that converts energy and usually consists of three parts: the injector assembly, the combustion chamber, and the exhaust nozzle. Azeite and the propellant mixture are divided into small droplets by an ionising region to mix at the start. Coaxial injectors adjust the size of the droplet and momentum ratio by means of recess ratio and momentum ratio [1]. The combustion chamber needs to be long enough for the chemical reaction to occur, and its characteristic length is used to determine the size of the chamber volume. The nozzle is a De Laval type, and by means of convergent-divergent shape, the speed of combustion gas reaches supersonic speed.

The power device that is required for the high-pressure staged combustion cycle and the staged combustion cycle is the turbopump feed system. The turbine is driven by the hot combustion gases from either a gas generator or a preburner, and then it powers the propellant pumps to increase the pressure of the propellants for injection. As Cai and others have pointed out [2], there is a close link

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between the staged combustion cycle and the turbopump assembly and the thrust chamber; a change in the preburner mixture ratio affects both the turbine power output and the inlet conditions of the main combustion chamber at the same time.

The working fluid of the gas generator or preburner supplies the turbopump. The gas out of the generator drives the turbine in a gas generator cycle and is then either discharged separately or added to the latter part of the nozzle. In a staged combustion cycle, all the gas from the preburner enters the main combustion chamber for secondary combustion; although it is more complex, it has a higher specific impulse than the gas generator cycle.

Valves and regulators are used to adjust the flow rate and pressure of propellant at various stages in the operation cycle of the engine to achieve smooth starting, stable running and shutting down. Thrust control is based on the response characteristics of the flow control valves, and mixture ratio control requires the joint operation of the oxidizer and fuel valves. The three main Design criteria for the speed of response, sealing ability and material compatibility of the valve are [3]. The propellant feed line connects the outlet of the tank to the inlet of the thrust chamber, and it will be subjected to high pressure, high temperature and vibration. The main engine of the Space Shuttle is a staged-combustion cycle, and to deal with the problem of high-frequency instability, baffles and acoustic cavities have been introduced [4].

2.2. Structure of solid rocket motors

Solid rocket motors have a simple structure, are easily stored for a long time and start quickly. The first Design Idea is to place the fuel-oxidizer and combustion Chamber in the same Housing.

The chamber case is the main load-bearing structure, and it is generally made of high-strength steel, titanium alloy or filament-wound composite materials. There should still be a relatively large internal pressure and external air drag. Composite motor cases have good specific strength, but the winding angle, fibre volume fraction and resin matrix properties need to be verified strictly [5].

The geometry of the propellant grain governs how the burning surface area changes with time, which in turn prescribes the thrust–time profile. Grain geometry dictates the thrust-time profile—neutral, progressive, or regressive—by controlling how the burning surface area evolves during combustion. In the Space Shuttle SRBs, a segmented grain was used [6], with a finocyl forward segment and a star aft segment providing the predesigned high-thrust-at-liftoff and later thrust-decay characteristics.

Due to the severe erosion caused by high-temperature, high-speed gas and entrained solid particles, the nozzle throat should be made of graphite, carbon/carbon composites or a refractory metal. The gradual increase in the diameter of the ablation end should be included in the internal ballistics calculation. The three parts of the ignition device are an electric firing squib, an igniter charge and a charge container. To achieve reliable ignition, the amount of igniter charge must be reasonable, the rate of energy release needs to be suitable, the location of the igniter should be appropriate, and so on.

2.3. Other propulsion system structures

The two tanks of a hybrid rocket are used to store the solid fuel grain and the liquid oxidizer; at a certain time, by adjusting the flow from a feed line and injector, the oxidizer is added to the combustion chamber to create a diffusion flame at the fuel-air interface. Cai et al. [2] found that the first problem in applying it is a small fuel regression rate; therefore, the present ways to expand the burning area include multi-port fuel grains and swirl injection.

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Hall thrusters are a type of electric propulsion that have an annular discharge channel and an axial electric field between the anode and the cathode. In the presence of a radial magnetic field, there is a Hall drift that can ionise and accelerate the propellant [7]. The lifespan of the thruster is mainly limited by the shape of the magnetic field and the sputter-resistant properties of the discharge channel wall material [7]. In an ion thruster, a grid is used to extract and accelerate ions; therefore, the two primary structural design problems that need to be solved are alignment accuracy and thermal deformation control of the ion optics. Ion thrusters have grids that extract and accelerate ions; the lifetime is affected by the grid material and thermal distortion [7]. Now, it is a carbon-based composite material for the accelerator grid that has reduced the sputtering yield of the old molybdenum grid.

3. Combustion characteristics of aerospace engines

Combustion characteristics refer to how efficiently the chemical energy of propellant is converted into the heat and motion of hot combustion gases, and also include its stability over time. The propulsion systems are not the same; they have different modes of combustion organization, underlying mechanisms and ways of releasing energy.

3.1. Combustion characteristics of liquid-propellant rocket engines

The Combustion Process in a liquid rocket engine has several stages of the propellants within the thrust chamber, such as atomisation, vaporization, mixing and chemical reaction. The Time Scales of these processes are different and are mutually linked.

Atomisation is a problem caused by the injector and propellant. A gas-liquid coaxial injector has a conical-spray-former in the centre that is extruded for spray, and it has the characteristics of spray cone angle, Sauter mean diameter and droplet size distribution. Large drops are not fully evaporated and therefore do not combust [8].

The Mixing process is related to the distribution of the spray field in the combustion chamber and turbulent diffusion. Combustion efficiency is defined as the ratio of the actual temperature rise to the theoretical temperature rise, and its relationship with mixture ratio and injector pressure drop can be expressed as the equation The atomization process is determined by the characteristic curve of combustion efficiency.

The problem of combustion stability in the development of liquid rocket engines is very serious. High-frequency combustion instability is a positive feedback coupling of acoustic modes and heat release oscillations, and it can cause a sudden increase in the local wall heat flux over a short time. Wang and others [9] believe that baffles and acoustic cavities are simple passive means to reduce high-frequency oscillations. Baffles divide the large area of the acoustic environment into many small sections and absorb sound energy at some frequencies in the acoustic cavities.

3.2. Combustion characteristics of solid-propellant rocket motors

Solid rocket motor combustion is characterized by the heating and decomposition of oxidizer and fuel components in the solid state before they enter the gas-phase diffusion flame. The basic number in the internal ballistics formula is the burning rate, which has the form $r = aP^n$. To maintain good internal ballistic stability, the pressure exponent n should be less than 1 [10]. If n is close to 1, a small pressure perturbation will grow into combustion instability.

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Combustion instability in solid motors is manifested by the coupling of acoustic modes and heat release at the burning surface. The response function of solid propellant to pressure oscillations is an indication of instability, and it represents the amplitude of burning rate fluctuation per unit pressure amplitude. The Response function is a function of operating frequency, average chamber pressure and other parameters of the propellant. Structural vibration and pressure oscillation can also form a coupled loop; that is to say, the elastic deformation of the casing changes the flow passage cross-sectional area and thus affects the pressure oscillation.

3.3. Characteristics of combustion and energy conversion in other engine types

Combustion in a hybrid rocket motor is a diffusion flame at the surface of the solid fuel, and oxidizer is transported from the core flow to this fuel surface by diffusion [10]. Therefore, it has a much lower regression rate than that of solid propellants [10]. Heat and mass transfer in the boundary layer determine the rate of fuel regression, and the oxidizer mass flux index is the main factor affecting the burning speed. The combustion stability of hybrid rocket motors is better than that of liquid rocket engines, and they are almost free of high-frequency instability.

The power source of the electric drive is converted into electrical power via ionization of the fuel. Ionisation efficiency is the proportion of input power converted into the kinetic energy of ions; it is mainly determined by the strength of magnetic confinement and discharge voltage. The angle of plume divergence affects the direction of thrust.

4. Structure and system of combustion

The Structure and Combustion Properties of a Spacecraft Engine are Interdependent. The structural parameter is the combustion organisation pattern and the rhythm of energy release; at the same time, the thermal and mechanical loads during combustion are constraints on the structure.

4.1. Combustion organisation mode

The Structure of the injector determines the initial distribution of propellant components in the thrust chamber. A gas-liquid shear coaxial injector can change the angle of the spray cone and the size distribution of droplets by altering the length of the recess, the width of the annular gap and the relative velocity of gas and liquid. The Strut in the combustor of a scramjet and a combined-cycle engine serves to inject fuel and stabilise the flame. The shape of the upper end and sweep angle determine the size of the separation zone and the strength of recirculation; at the same time, the arrangement of fuel injection holes affects how deeply the jet enters and how uniform the mixing is. Hui Bo and others [5] have shown that to improve the ignition characteristics and burnout rate of boron particles in a short axial distance, one can optimise the strut layout.

4.2. Energy release regulation

The thrust program of a solid rocket motor is predetermined by the grain structure, and the relationship between thrust and time changes according to the expansion of the burning surface along the combustion path. Grain patterns are stars, slots and finocyl; each will have a different amount of thrust and gradient. Throttling technology of the liquid rocket engine is a type of flow control valve and variable injector orifice area that can adjust the speed of propellant flow and chamber pressure dynamically. The accuracy of thrust throttling ratio and mixture ratio control is limited by the performance of valve actuators.

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4.3. Combustion stability and structure

The Shape of the combustion chamber determines some of the natural frequencies of sound. When the heat release oscillation is at the frequency of an acoustic mode and meets the phase condition for the Rayleigh criterion, combustion instability will occur. Suppression devices change the shape of the acoustic boundary; often, there are many small rooms in the baffles to reduce tangential modes, and acoustic resonators can be used to selectively absorb frequencies by adjusting the size of their neck and the volume of the backing cavity. Farokhi [8] has been studying the effect of baffle height on the acoustic field in the combustion chamber from an aerothermal perspective. Solid rocket motors have unstable combustion due to the coupling of structural vibration and pressure oscillation. The basic reason is that there is a closed-loop feedback circuit formed by the elastic mode of the casing and the acoustic mode of the chamber through the burning rate response function. In recent years, in addition to the old passive control method, active control and real-time monitoring of combustion instability have been studied. First, dynamically tunable acoustic boundaries are used; that is to say, a deformable baffle driven by piezoelectric actuators or shape memory alloys can change the acoustic damping characteristics based on different spectra of pressure oscillation. Second, a machine learning method can be used to extract acoustic mode features from the chamber by means of a high-frequency pressure sensor array, and then a deep learning model is used to predict the early stages of instability; together with a flow control valve, it is possible to achieve closed-loop active suppression. Wang and his colleagues [9] have found in their study that a model for predicting oscillation can be based on a convolutional recurrent neural network (CRNN) to anticipate the beginning of instability tens of milliseconds in advance and provide a window for active control.

4.4. Structure in the extreme heat environment

There are many kinds of heat transfer on the wall of the thrust chamber, such as convection, thermal radiation, and possibly thermochemical ablation; thus, it has a very high temperature. The design of the thrust chamber and nozzle must be able to withstand the high temperatures. The heat transfer boundary conditions for the design of the thrust chamber in the active cooling system are the phase change of coolant and the critical heat flux limit. New thermal insulation materials are being researched to address problems in the Design of Thrust Chambers and Nozzles. Ultra-high-temperature ceramics (UHTCs), such as ZrB_2-SiC and HfB_2-SiC composites, have good oxidation and ablation resistance at temperatures above 2000 °C, so they are now considered new replacements for traditional C/C composites in nozzle throat inserts. Continuous-fibre-reinforced ceramic matrix composites (CMCs), such as SiC/SiC, have shown some results in the application of regeneratively cooled chamber walls; although they have a relatively low density compared with metals, they still have good high-temperature properties, and therefore only a small amount of coolant flow may be needed. To reduce the magnitude of the coefficient of thermal expansion and improve oxidation resistance, graded-coat technology is employed to add a transition layer of SiC and a UHTC outer layer on top of the surface of C/C composites incrementally. Copper alloy cooling channels can be manufactured through selective laser melting (SLM) additive manufacturing, have contoured cross-sections and graded fin structures, are about 20-30 per cent better in terms of heat transfer than those milled by other means, and have reduced flow resistance.

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5. Conclusion

Considering the main problem of the coupling between structure and combustion characteristics, four types of space propulsion engines have been studied in depth through literature comparison and general analysis in this paper. Based on the above analysis, the structural parameters are the boundary conditions for combustion; a small change in the recess ratio or strut sweep angle of the injector can alter the initial mixing and flame stabilization of the propellants, and at the same time, the shape of the chamber affects both the characteristic length and acoustic natural frequency, so when the heat-release zone is in alignment with an acoustic pressure antinode and meets the Rayleigh criterion, baffles and acoustic cavities can be used selectively to suppress certain modes by adjusting acoustic boundaries. The quantity and velocity of the coolant in the regeneration channel will affect how much heat is released near the wall for heat insulation; a small change in the thrust coefficient due to various throat areas caused by throat insert erosion can initiate a chain reaction of heat transfer, ablation and loss of aerodynamics. The above are connected; at the same time, there is an overall structure and governing physics for combustion.

The future direction of research will be as follows. First of all, a whole-chain multi-physics simulation model should be constructed that covers injection atomisation, turbulent combustion and wall heat transfer; thus, this paper will be able to know how changes in structural parameters affect combustion efficiency and the thermal environment. Second, in light of the problem of erosive burning in solid motors and the ignition-to-burnout mechanism of boron-laden fuel-rich propellants, an experimental database of burning rates and response functions at a large number of different pressure and temperature conditions needs to be established to calibrate the internal ballistic prediction model. Thirdly, there is still much that needs to be explored in the use of additive manufacturing technology for constructing complex regenerative cooling channels and non-traditional throat insert shapes; also, how to improve the heat transfer performance and enhance the flow characteristics of non-conventional configurations has not been investigated yet. The above will advance the development of space propulsion engines in the direction of high specific impulse, high reliability and reusability.

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