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FOREIGN TECHNOLOGY DIVISION

AIR FORCE SYSTEMS COMMAND

ROCKET ENGINES

by

KE Bi-tien

FOREIGN TECHNOLOGY DIVISION

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ROCKET ENGINES

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ROCKET ENGINE

PART 2 Solid and solid-liquid rocket engine

Author: KE Bi-tien

THIS ARTICLE DISCUSSED THE COMPOSITION, PROCEDURES, ADVANTAGE, DISADVANTAGE, DEVELOPMENT AND APPLICATION OF SOLID ROCKET ENGINE AND SOLID-LIQUID ROCKET ENGINE. THIS IS THE THIRD OF A SERIES OF ARTICLES WHICH CONSECUTIVELY INTRODUCED ROCKET ENGINE. THE FORMER TWO ARTICLES HAD BEEN PUBLISHED IN THE ISSUES OF MONTHS OF AUGUST AND SEPTEMBER OF THIS MAGAZINE.

A solid rocket engine is so named because its propellent is solid under normal conditions. The following four portions are introduced, these four portions are: the main parts, work process, main advantages and disadvantages, and the brief history of its developments. Finally we then simply introduce the solid-liquid rocket engine.

IMPORTANT PARTS

Solid rocket engine is mainly composed of solid gun powder grain, combustion chamber, nozzle and ignition installation. Fig. 1 is a typical structural diagram of a solid rocket engine. In addition to the above mentioned important parts, an entire modern solid engine must have: grain supporter, dehumidifier, combustion chamber pressure safety device, thrust directional control device and thrust stopping device. Only the important parts are introduced as follows.

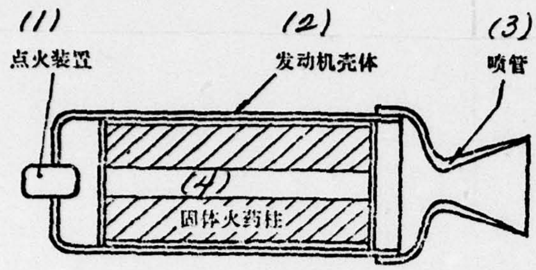

Fig. 1. Typical solid rocket engine structural diagram.
Key: 1. Ignition.
2. Shell of the engine.
3. Nozzle.
4. Solid gun powder grain.

Solid gun powder grain is made of solid propellant by means of certain technology. Solid propellent contains necessary chemicals to maintain the chemical combustion, it looks like plastic, and generates a large quantity of gas after it is burned.

The propellant that composes the solid gun powder grain is generally divided in two categories, one is the nonhomogeneous, also called the compounded propellent; another is the homogeneous type. For instance, use the crystalline perchlorate as oxidizer and mix it in the plastic organic combustible component to make propellent, such propellent belongs to the nonhomogeneous type; and the homogeneous type usually refers to the double base powders (which are nitro-cotton and nitroleum). Other types of propellents are black powder and the propellent composed by the homogeneous propellent and certain elements of the nonhomogeneous propellent. In order to improve the combustibility, mechanical, physical and chemical properties of the propellent, some supplemental ingredients are often added during the manufacturing of the gun powder grain. In order to limit the combustion area of the grain, the naked surface of the grain is covered with a layer of inhibitor.

For a well designed and manufactured grain, it burns homogeneously on the naked surface after the ignition; it should not have any serious unstable combustion nor have explosion.

Furthermore, it should have a certain degree of physical and chemical stability. Some propellents are affected by temperature, they have more thrust in the hot days than in the cold days; the combustion speed is also increased; the pressure in the combustion chamber is also increased; but the combustion time is correspondingly decreased. This illustrates that the initial temperature of the grain has a definite effect on the combustion time. When the temperature is very cold, the grain is brittle. Some grains may then crack when ignited. When the temperature is too hot, the strength of the grain decreases. All of the above conditions could increase the combustion area and induce an explosion of the propellent, and thus damage the engine. Pressure has also a large effect on the combustion of the propellent grain; too high a pressure will speed up the combustion very rapidly and cause the combustion chamber to crack; too low a pressure will not be able to stabilize the combustion. In fact, some propellents could not continue their combustion under atmospheric pressure. Such problem should be solved during the design and manufacturing of the engine and its propellent grain.

Generally, the combustion chamber is cylindrical and both ends are hemispherical. The materials used are high strength alloy steel and glass steel; titanium alloy is also used. The combustion chamber is where the powder grain is installed, it should have sufficient strength to the high pressure produced during the combustion of the powder grain. Thus, a layer of insulation is installed on the inner wall when the compound type propellent is used. Under the condition of mission accomplishment, the weight of combustion chamber should be as light as possible, so that the performance of the flying vehicle is improved. Fig. 2 is the configuration of the first stage solid rocket engine of an intercontinental ballistic missile; the front is the combustion chamber, and the back are four rotating nozzles.

The nozzle could cause the high-temperature and high pressure burning gas in the combustion chamber to expand and to form a

Fig. 2. The picture of a solid rocket engine of a ballistic guided missile.

near-ambient-pressure and high-temperature supersonic efflux to produce the thrust. Fig. 3 shows an experimental rotating nozzle of a large solid propellant rocket engine. The nozzle of solid rocket engine is a nozzle without cooling system; its shell is made of alloy steel or glass steel. The inner surface has to be flushed by a high speed hot burning gas stream; therefore an insulation liner should be installed. The throat is another key portion of the nozzle, so the insulation liner is especially important. Presently the insulation materials used in the solid-propellent rocket engine are phenolic resin, carbon cloth, silicon cloth combined material, hard-melting metal, ceramics, etc. One chamber may have a nozzle; several nozzles may also be installed.

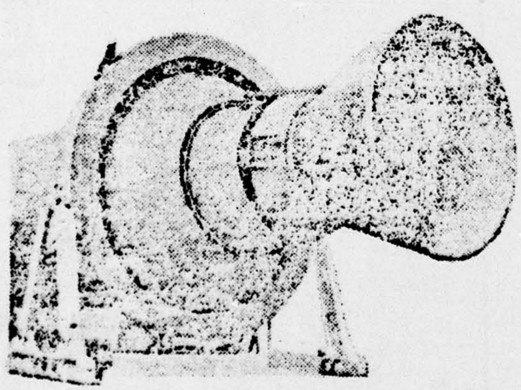

Fig. 3. The rotating nozzle of a large solid rocket engine.

The function of the igniter assembly could be installed in front of the combustion chamber, or in the middle, or at the rear. The igniter assembly is composed of electrically heated wire, primer powder charge, and the igniter housing. After the ignition signal is given, the electricity is turned on, the wire burns hot, and the sensitive primer powder charge burns and ignites a larger main igniter charge which generates high-temperature flames and ignites the solid propellent grain.

THE OPERATING PROCEDURE OF SOLID PROPELLANT ROCKET ENGINE

The operating procedure of a solid propellant rocket engine is much simpler than that of the liquid propellant rocket engine. To start the engine, first start the igniter by electricity; then the flame of the igniter ignites the propellent grain in the combustion chamber. The high-temperature and high-pressure burning gas expands when it passes through the nozzle, then escapes with high speed, and generates the thrust.

Everyone knows that in order to keep the fuel burning, a certain proportion of oxidizer must be used to aid the combustion. Under the condition of no external influence, the fuel must have adequate contact with oxidizer, the better they mix, the more stable and complete the combustion is. The combustion of a non-homogeneous solid propellent, after its elements had been determined, depends largely upon seeing that the mixing of the fuel and a certain proportion of the finely ground oxidizer is homogeneous. In the double-base propellent there is sufficient oxidizer in the molecular structure; such propellent can maintain the combustion by itself. The thrust of a rocket engine is proportional to the exhaust flow of the nozzle. When the solid propellent engine is in operation, the combustion moves perpendicularly to the combustion surface along the grain. The larger the combustion area of the grain, the larger the amount of burning gas generated in a unit time, the greater the flow of burning gas passing through the nozzle, and the more the thrust increases. Conversely, the smaller the combustion surface of the grain, the smaller the thrust.

Obviously, under the condition that the propellent has the same ingredients, the thrust of the solid propellent engine is determined by the combustion surface of the grain. According to this characteristic, a change of the combustion surface of the solid propellent grain could result in a change of the thrust of the solid propellent rocket engine. For example, Fig. 4 shows the booster solid propellant rocket engine of a huge carrier rocket. Its solid propellent consists of three portions: five middle sections are internal hollowed conic shaped propellents, one rear section is an internal hollowed cylindrical shaped propellent, one front section is an internal hollowed star configurational propellent. These propellents have the characteristics of progressive reduction of thrust in order to meet the requirement of the structural strength of the mid section of the carrier rocket. The combustion surface of the propellent may also change during the combustion; the combustion which increases on the burning surface is called progressive burning, the one which decreases on the burning surface is called degressive burning, and the one which maintains a constant surface is called neutral burning. The cross sections of

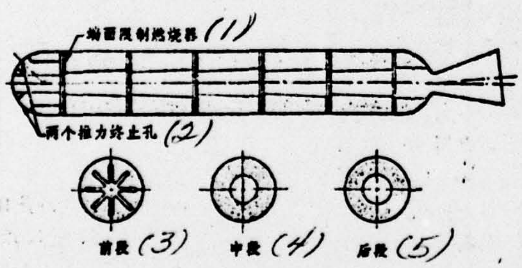

Fig. 4. Booster solid propellent rocket engine of a large carrier rocket.

Key: 1. The end limiter of combustion.
2. Two thrust stopping holes.
3. Front stage.
4. Middle stage.
5. Last stage.

these three types of propellent are shown in Fig. 5. Furthermore,

Fig. 5. Cross section configurations of three types of grains.
1. Increasing surface combustion (single perforated).
2. Decreasing surface combustion (star perforated).
3. Neutral combustion.

both methods of covering the naked surface of the propellent with non-combustive inhibitor or changing the ingredients of the propellent could also vary the thrust. The combustion surface not only affects the thrust, but also affects the pressure of the combustion chamber and the operating time of the engine; under the circumstances that all other conditions remain the same, the larger the combustion surface, the higher the pressure in the combustion surface, the higher the pressure in the combustion chamber, and the shorter the operating time. On the other hand, reducing the combustion surface, the pressure of the combustion chamber will be reduced and the operating time will be prolonged.

THE MAIN ADVANTAGES AND DISADVANTAGES OF A SOLID PROPELLANT ROCKET ENGINE

After comparing the liquid propellent rocket engine and solid propellent rocket engine, we can see that the advantages of the solid propellent rocket engine are that the system is simple, it does not have the pump, valve, gas producer, etc.; it does not have an injector. Thus the structure of the engine is much simpler and the operation is more reliable. The density of the solid propellent is high; the solid propellent grain is loaded in the engine beforehand. Therefore the time of battle readiness is short, which is advantageous in the battle; there is not much maintenance. Because of these advantages, the solid propellent engine is widely used in the military.

The solid rocket engine also has some disadvantages, among which are that the consumption of the propellent is uncontrollable and the engine is not reusable. Second, some solid propellents are greatly affected by temperature; it is rather difficulty to satisfy the requirements of the ambient condition as the guided missile is required to work under a larger temperature range. Another disadvantage of the solid propellent rocket engine is that the center of gravity of the engine shifts greatly from one point at the time of launching to another at the time of extinguishing of the engine. At the present level, generally speaking, the specific impulse of the solid propellant is lower than that of some liquid propellents, and the operating time is also shorter. These disadvantages limited the application of the solid propellent engine for space flight.

THE DEVELOPMENT OF THE SOLID PROPELLANT ROCKET ENGINE

Our country is the earliest country which invented the solid propellent rocket. According to the record, in the seventh century the black powder was invented in Tang Dynasty. The military men in the Sung Dynasty had started to use powder as a weapon. They tied the powder on the arrow and called it rocket. There was a flying bomb made in the Ming Dynasty. It is a ball 3 to 4 inches in diameter and is filled with two sections of powder. When the lower section is ignited, it flies to the enemies' battlefield, then the upper section explodes to wound and kill the enemies.

Black powder was spread to Europe through the Arabians in the Yuan Dynasty.

The rocket projectile made of the black powder appeared in England in the year 1800. At the end of 19th century, because of the increase of the accuracy of hitting by gun, the development of the rocket projectile had almost stopped. During the World War II, the study of the rocket projectile started again, improvements were made, and the rockets were widely used during the war. At the end of the forties and in the fifties of 20th century the liquid propellent engines developed very rapidly; basicly the mid-range guided missiles were using the liquid propellent rocket engine during that period of time. At the end of the fifties, there came out a solid propellent with a high specific impulse (close to 250 seconds), the success of the new moulding technology of propellent grain, and the improvement of the surface design of the propellent grain, all of which had created favorable conditions for making the large solid propellent rocket engine. The first solid propellent ballistic missile "Jones" was made during this period. Nearly all tactical missiles use solid propellent rocket engines. In the 1960's, the performance and the thrust of the solid propellent rocket engine were fruther improved in addition to the fine military operational performances; hence the solid propellent rocket engine had been developed into the main power installation of the mid-range guided missile and ballistic guided missile. In space flight, the solid propellent rocket engine is used in some large flight vehicles as an auxiliary booster. Some small solid propellent rocket engines are also used in the carrier as the stage separator and in the orbit-changing of the satellite. Even some fighter aircraft use the solid propellent rocket engine as an assisting take off unit for improving the operational performance of the fighter.

The important point of developing the solid propellent rocket engine is the research of the solid propellent. At present, the adhesives used in the solid propellent mainly are polyurethanes and polybutadienes; the oxidizing agent is mainly ammonium perchlorate; additive is aluminium powder, etc. The important means of increasing the energy of the solid propellent is to use new oxidizing agents, new adhesives and light metal additives. In the area of oxidizing agent, the main research is on the fluorooxidant, the perchlorate with strong oxidizing power, high-nitrogen oxidate, etc. There are two directions in developing the adhesives: one is to introduce the oxidizing radical into the molecular structure of the adhesive, such as nitrate radical, nitro-group, perchloric acid radical, etc.; another is to introduce the high energy radical, such as kuai*, boric alkyl, etc. (*no chemical meaning available.) Presently the additives which are in research are mainly beryllium, beryllium-lithium alloy, aluminium hydride, etc.

A special characteristic of the foreign modern large solid propellant rocket engine is to manufacture it by sectional casting and then assemble the whole thing; thus, it is convenient to make, transport and use. Now the ones which are under study are the solid propellent engine with a diameter of 3 meters and of 6.6 meters, and a study to make an engine with a diameter of 8 meters is under way. Presently the solid propellent rocket engine with a diameter of 3 meters and five sections is the largest engine in use. It is used in the carrier rocket as a booster. Its main parameters (single stage) are about 500 tons of thrust, about 120 seconds of burning time, 123 tons of propellant, about 230 tons of the engine, approximately 26 meters long. The specific impulse of the solid propellent rocket engine used at present reaches as high 250 seconds.

Most of the thrust stopping mechanisms of the engines use the explosive type device and reverse directional device. Most of the thrust vector controls of the engines use the rotating-nozzle and the two-injection methods. Also, other methods such as three-injection are in the state of research.

SOLID-LIQUID PROPELLANT ROCKET ENGINE

Solid-liquid propellant rocket engine is one of the composite rocket engines. The composite rocket engine usually means that the propellent used by this type of engine is composed of materials of solid and liquid state under normal conditions. The composite engines usually have solid-liquid, liquid-solid types, etc. The liquid-solid engine means that the fuel is liquid and the oxidizing agent is solid for the engine. This types of engine has not been studied much because the energy of the solid oxidizing agent is not high enough, and it is difficulty to form the commonly used solid oxidizer into grains.

The solid-liquid engine means that the rocket engine uses solid fuel and liquid oxidizer as propellent (Fig. 7[sic]). Due to the fact that most high energy fuels are solids, most high oxidizers are in liquid form.
The solid-liquid propellent engine can fully utilize the energy from these elements and therefore, draws more attention. It occupies an important position in rocketry, and is also the kind most studied.

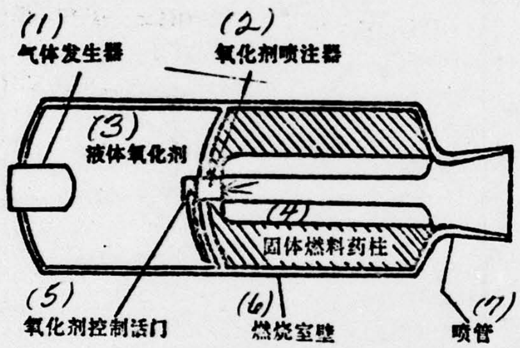

Fig. 6. Solid liquid rocket engine structural diagram.
Key: 1. Gas generator.
2. Oxidizer injector.
3. Liquid oxidizer.
4. Lolid fuel grain.
5. Oxidizer control value.
6. Wall of combustion chamber.
7. Nozzle.

Fig. 6 shows the solid-liquid engine with an injector in the head. The liquid oxidizer of this kind of engine produces gas by means of the gas generator. The pressure of the gas increases, until it reaches at certain pressure. It is injected into the perforation of the solid fuel grain from the head of the engine, and starts burning inside the perforation (commonly pyrophoric by contact); the burning gas passes through the nozzle and produces the thrust.

Each of the solid engines and liquid engines has its own ad vantages, but the solid-liquid engine has combined some advantages of both. For instance, for performance, the specific impulse is higher than the solid engine and is comparable with the storable liquid rocket engine but lower than the high energy liquid rocket engine. The theoretical specific impulse of the solid-liquid propellent is approximately between 200 to 400 seconds. The system and the structure of the engine are simpler than the liquid rocket engine but more compactly put together; the density of the propellent is higher than that of the liquid propellent. The fuel grain and the oxidizer of the solid-liquid engine are separated before working; therefore, the slow chemical change does not happen during prolonged storage as with the solid propellent grain, and also it does not cause combustion nor explosion when accident happens. By utilizing the adjustability of the flotation of the liquid oxidizer the thrust, the starting and the cut-off of the solid-liquid rocket engine are controllable. By using the oxidizer cooling nozzle the life of the nozzle could be extended. If the oxidizer of the solid-liquid engine could be stored, the combat effectiveness would be greatly increased. Of course the solid-liquid engine also has its disadvantages which are mainly low burning efficiency, the mixing rate can not be easily obtained when engine is at work, a large amount of energy is lost when the thrust is adjusted, the high energy composite propellent is poisonous, etc. According to these, it is obvious that the performance of the solid-liquid engine is theoretically better and the application range should exceed the solid rocket engine; however, it is not popular due to the unsolved existing problems.

The principle of a solid liquid engine was mentioned in 1933. The Soviet Union and the United States have performed a lot of research work in the solid-liquid engine since the 1950's which resulted in a number of small rockets with this type of engine as the power plant.

The development of the solid-liquid rocket engine is mainly to increase the performance of the propellent. Light metals and the hydrogenates which release a large amount of heat during combustion and produce a small quantity of gas molecules are tried in the development of high energy solid-liquid propellent.

The three-section-unit propelling system is one important development of the solid-liquid rocket engine. It utilizes the method of injection of the hydrogen into the system for reducing the molecules of the burned gas to increase the specific impulse to more than 500 seconds.

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