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MODELING AND NUMERICAL SIMULATIONS

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INTERNAL COMBUSTION PROCESSES OF LIQUID ROCKET ENGINES

Preface

Liquid rocket engines are the main propulsion system for a spacecraft. The widespread applications of liquid rocket engines in the future demands further studies of combustion mechanisms in liquid rocket engines to improve their performance. Numerical modeling of the combustion process can improve our understanding of the incorporated physical mechanism and help in the design of liquid rocket engines. Since the 1970s, numerical simulations of combustion in liquid rocket engines have developed into a new interdisciplinary subject involving computational fluid dynamics, computational heat transfer, computational combustion, software design, and flow visualization. Owing to its significance in engine design, this new subject has attracted many researchers. With the rapid development of computer techniques and numerical methods, numerical modeling and simulations of atomization and combustion in liquid rocket engines will become an ever important research area.

The author has dedicated himself to the area of Aeronautical and Astronautical Science and technology since the 1980s. The present book is based on the teaching and supervision of undergraduate and postgraduate students in the past 30 years. The book highlights the advanced research work in the field of combustion modeling in liquid rocket engines, such as liquid propellant atomization, evaporation of liquid droplets, turbulent flows, turbulent combustion, heat transfer, and combustion instability. All these will contribute to our understanding of the combustion mechanism and to the improvement of combustion modeling, facilitating numerical simulations of combustion process in liquid fuelled engines.

The book consists of eight chapters. Chapter 1 describes the configuration and fundamentals of liquid rocket engines, and presents an overview of numerical simulations of combustion in liquid rocket engines. Chapters 2–7 detail the modeling of combustion sub processes in liquid rocket engines, i.e., atomization modeling, evaporation modeling, turbulence modeling, combustion modeling, heat transfer modeling, and combustion instability modeling. Chapter 8 presents a full description of numerical models for combustion, numerical methodology for governing equation solution, and grid generation. Finally, three applications are run to demonstrate the capability of the numerical models to predict the combustion process in liquid rocket engines.

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Introduction

A liquid rocket engine, which is also called a liquid propellant rocket engine, is a chemical rocket engine using liquid chemicals (liquid propellant) as the energy source and the working fluid. Liquid rocket engine technology has drawn researchers' attention and been quite a hot topic in aerospace and aeronautic research during the last 70 years. In the short long history of human aviation, i.e., from the A-4 engine of the German V2 missile, to the F-1 engine of the U.S. lunar landing rocket "Saturn 5" and further to reusable space shuttle main engines, every milestone event is closely linked with the progress made in liquid rocket engine technology. Because liquid rocket engines have the characteristics of high specific impulse, repeatable starting, arbitrary working hours setting, multiple usage, adjustable thrust, etc., they are bound to occupy the dominant position in the area of aerospace propulsion long into the future.

The liquid rocket engine uses liquid fuels as the propellant. In a liquid rocket engine, the liquid chemical propellants combust in the combustion chamber and produce very high pressure gas. The gas is accelerated when it flows downstream through the nozzle and produces impulse, i.e., thrust, for the aircraft. There are several types of liquid propellants. The scheme, structure, ignition and thermal protection, etc. of the liquid rocket engine have a close relationship with the characteristics of the propellants used by the engine system.

The expansion of liquid rocket application requires more in-depth studies on the basic theory and design method of the liquid rocket engine. Numerical simulation of the combustion process in a liquid rocket engine is also an important research direction. This chapter introduces the basic configuration and working process of liquid rocket engines, and then discusses the main objective and research method of the numerical simulation of the combustion process in a liquid rocket engine.

Internal Combustion Processes of Liquid Rocket Engines: Modeling and Numerical Simulations,
First Edition. Zhen-Guo Wang.

1.1 Basic Configuration of Liquid Rocket Engines

A liquid rocket engine consists of a thrust chamber (which consists of an injector, a combustor, and a nozzle), a propellant feed system, propellant tanks and various automatic regulators, etc. This section mainly introduces the propellant feed system and the thrust chambers, which are closely associated with the combustion process.

1.1.1 Propellant Feed System

The propellant feed system is employed to deliver the propellants from the containing tanks to the thrust chamber and can be divided into two categories according to the working mode, namely, the pressure feed system and the turbo-pump feed system.

1.1.1.1 Pressure Feed System

The pressure feed system pushes the propellants to the thrust chamber or the propellant gas generator by the high pressure gas in the tanks of the propellants. The high pressure gas, i.e., the pressed gas, can be pre-stored in cylinders as the storage gas and can also be generated by a liquid or solid gas generator during the working process of the liquid rocket engine. The main requirements for the pressed gas are as follows: (i) high density while under the pressed state, (ii) low relative molecular mass under the pressed state, (iii) minor solubility with propellant, (iv) no or minor chemical reaction with the propellants, and (v) no solid and liquid impurities.

The pressure feed system can employ inert gases as the pressed gas. This kind of pressure feed system has two type of working mode, namely, the regulated pressure mode and the blow-down mode. The former employs a pressure regulator to maintain the pressure in the propellant tank, and also maintains the thrust at a constant value. The latter stores the propellant and the pressed gas in one tank. The pressure drops during the adiabatic expansion of gas, fewer propellants are injected into the combustor and therefore the pressure in the combustion chamber also drops. Typical pressure feed systems are (i) those with high-pressure gas cylinders and (ii) those with gas generators. The former can employ air, nitrogen, helium, and some other inert gas as the pressed gas. The main drawback of air is that the contained oxygen has a relatively high boiling point, and therefore it cannot be used to press cryogenic propellants. Helium can be used to press all existing liquid propellants. Although such a pressure feed system has a relatively large size and heavy mass, it has the characteristics of a simple structure and high reliability. It is also simple to employ and ensures repeatable starting of the engine.

In pressure feed systems with a gas generator, a single-component liquid fuel gas generator using a monopropellant as the source of the driven pressure and the propellant decomposition can be realized by catalysis or heating according to the kind of propellant. In dual-component liquid fuel gas generators, the high pressure gas can be obtained from the two propellant components by burning under oxygen-rich or fuel-rich conditions. The temperature of the gas is determined by the propellant component mixed ratio in the gas generator.

The structure of the pressure feed system is simple and reliable. However, as the propellant tanks must withstand high internal pressure, the pressure feed system is relatively bulky and it is often employed by spacecraft-attitude-control engines. Sometimes, to ensure the reliability of manned flight, although the engine thrust is large, a pressure feed system is also employed, such as the service module engine, drop class, and upgraded engines of Apollo spacecraft.

1.1.1.2 Turbo-Pump Feed System

A turbo-pump feed system employs pumps to deliver propellants, and the pump acquires the driven force from a turbo. In the turbo-pump feed system, a turbo-pump assembly is necessary. The basic requirements for a liquid rocket engine turbo-pump are as follows:

1. If the mass flow rate of a given propellant is given, we need to ensure the pressure at the engine outlet matches the requirement of the engine system.
2. The turbo-pump should be as small and light as possible.
3. The turbo-pump is to have as high an efficiency as possible.
4. The turbo-pump should ensure stable operation at all engine operating conditions and the pressure pulsation and mechanical vibration must be minor.
5. The turbo-pump is to be compatible with corrosive liquid and cryogenic liquids. Friction is not allowed between the components of the oxidizer pump because the heat created by the friction may produce a local high temperature, even an explosion.
6. The turbo-pump is to be capable of sucking propellants that contain a small amount of gas or steam.

There are three common types of cycle program for the turbo-pump feed system, namely, gas generator cycle, expansion cycle, and staged combustion cycle. The gas generator cycle and the staged combustion cycle can employ most of the commonly used liquid propellants. The expansion cycle engine is commonly used in an engine that employs liquid hydrogen as thrust chamber coolant, because liquid hydrogen is a good absorbing-heat medium and it does not decompose.

In the gas generator cycle, the turbine inlet gas is from an independent gas generator, turbine exhaust gas by passing through a small area ratio turbine nozzle, or by injecting in the main stream of the engine through the opening of a nozzle divergence cone. The gas generator propellant can be monopropellant or bipropellant, both of which are from the main propellant feed system. Figure 1.1 shows the bipropellant gas generator cycle turbo-pump feed system; the fuel in the pump portion is injected into the bipropellant gas generator and combust, producing working fluid to drive the turbine. To make sure that the temperature of the combustion products in the gas generator is suitable for the requirements of the turbine, we need to control the propellant mixing ratio in the gas generator, and the gas temperature should be in the range 700–900 °C. Since a bipropellant gas generator system does not require an auxiliary propellant or another tank, its structure is certainly simple, and it is widely employed in liquid rocket engines.

The gas generator cycle is relatively simple. The pressure in the fluid pipes and pumps is relatively low. Therefore, it is the most commonly used turbo-pump cycle. For an engine using the gas generator cycle, the specific impulse of the thrust chamber is slightly higher than that of the engine. However, the thrust of the thrust chamber is always slightly lower than that of the engine.

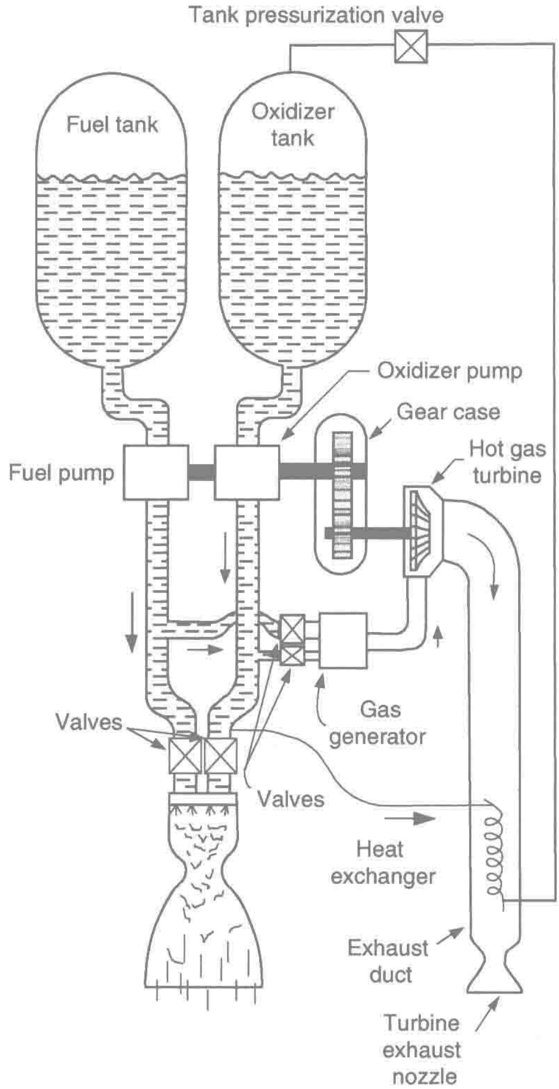

Figure 1.1 Bipropellant gas generator cycle turbo-pump feed system.

The expander cycle is typically used in an engine that employs liquid hydrogen as the fuel. An expander cycle turbo-pump feed system is shown in Figure 1.2. After absorbing heat from the cooling jacket, the liquid hydrogen becomes heated hydrogen gas. Before entering the main thrust chamber, hydrogen first drives the turbine, and then all the hydrogen gas is injected into the engine combustion chamber, mixed with the oxidant, and combusted. Further, the combustion gas is efficiently expanded in the nozzle and then exhausted. The expansion cycle has high specific impulse. Such an engine is also simple and relatively lightweight. However, the cooling jacket of the liquid hydrogen limits the amount of the absorbed heat, so that the turbine work capability is limited, thereby limiting improvement of the combustion chamber pressure. The pressure in the chamber is generally 7–8 MPa. If the chamber pressure is higher than 8 MPa, this cycle mode is not recommended.

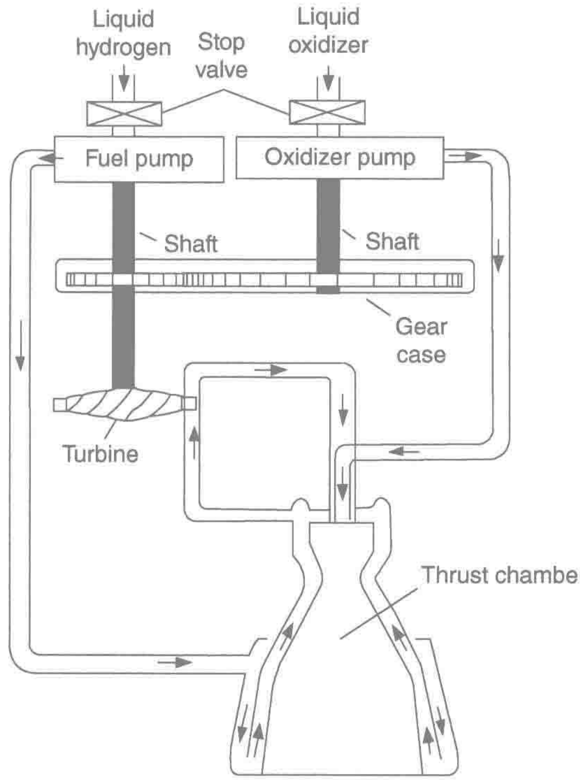

Figure 1.2 Expander cycle turbo-pump feed system.

Figure 1.3 shows a turbo-pump feed system with staged combustion cycle. In this system, the coolant and fuel firstly flow into a thrust chamber cooling jacket and then are injected into a high pressure pre-combustion chamber where the fuel combusts with part of oxygen. The combustion in the pre-combustion chamber provides the high energy gas for the turbine. After driving the turbine, the gas flows into the main combustion chamber, fully combusts with the oxygen, is exhausted, and is ejected through nozzle.

In a staged combustion cycle, the high pressure pre-combustion can be a monopropellant gas generator or bipropellant gas generator; we can adopt oxygen-rich pre-combustion, such as with the Russian RD120 engine (using liquid oxygen/kerosene propellant) and Russian RD253 engine (using nitrogen tetroxidizer/unsymmetrical dimethylhydrazine propellant). We can also employ fuel-rich pre-combustion such as used in the Space Shuttle Main Engine (using liquid hydrogen/liquid oxygen propellants). Because one of the propellant components goes entirely into the pre-combustion, the flow rate of the turbine working fluid is quite large, so that the turbine output power is greatly improved, and thus a high combustion chamber pressure is allowed to obtain high performance and reduce the size of the thrust chamber. The staged combustion engine has the highest specific impulse; however, the engine is the heaviest and most complex.

In the turbo-pump feed system, the turbine exhaust gas contains energy, and therefore it is possible to improve the specific impulse of the liquid rocket engine through using this energy. If the turbine exhaust gas flows into the liquid rocket engine combustion chamber, where it is

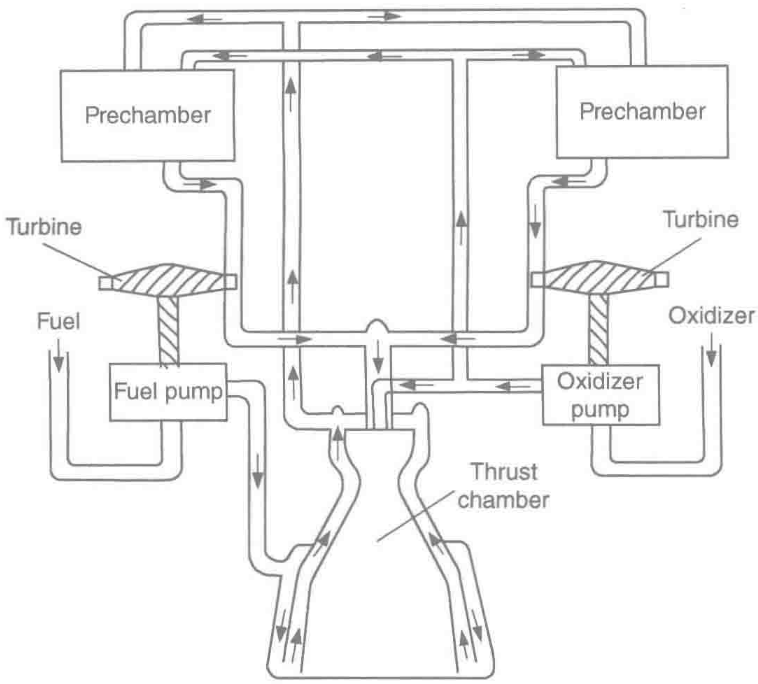

Figure 1.3 Staged combustion cycle turbo-pump feed system.

combusted with other propellants, this type of pump circulation is called a closed loop. If the turbine gas exhaust goes directly to the surrounding environment or goes into the main flow through the engine nozzle expansion opening section, then this pump circulation is called open cycle. Clearly, the gas generator cycle is an open-cycle, and the expansion cycle and the staged combustion cycle are closed loops. In contrast, an open-cycle engine is relatively simple, operates at low pressure, and the research and development costs are low; however, the closed cycle engine can achieve a higher specific impulse.

1.1.2 Thrust Chamber

A thrust chamber is a device in which chemical energy is turned into mechanical energy. Typically, a device in which chemical energy is converted into heat energy is called a combustion chamber while a device in which heat energy is converted into kinetic energy is called a nozzle. In addition to the combustion chamber and nozzle, a liquid rocket engine thrust chamber also has a unique component—the injector, which is located in the combustion chamber head. Propellant components are injected into the combustion chamber from the injector head, and then they atomize, evaporate, mix with each other, and combust in the combustion chamber. The chemical energy of the propellants is thus converted into heat, producing high-temperature, high-pressure gas. Then, the combustion gas eject from the nozzle at high speed after expansion and acceleration, producing thrust.

Since the thrust chamber works under harsh conditions of high temperature, high pressure, and high flow scour, its structure should satisfy the requirements of high efficiency (combustion efficiency and nozzle efficiency), stable working conditions (reliable ignition start, stable combustion), reliable cooling measures, and good economy (simple structure, light weight, good technology, and low cost), etc.

1.1.2.1 Constituents of a Thrust Chamber

Injectors

Injectors are usually located in the front of the combustion chamber. The function of the injector is to inject the propellants into the combustion chamber at a fixed flow rate, and let the propellant atomize and mix in a certain ratio to form a homogeneous mixture of fuel and oxidant to facilitate gasification and burning. The injector provides a cooling protective film to prevent the thrust chamber wall from being overheated. In addition, injectors also bear and transfer thrust.

The commonly used injectors can be classified into orifice injectors, swirl injectors, and coaxial tube injectors. Figure 1.4 shows the injector classification.

As shown in Figure 1.5, for an impinging stream pattern, propellant is ejected from numerous independent small holes. The fuel and oxidizer jets then collide with each other, after which a thin liquid fan is produced, which helps the liquid atomize into droplets and helps to produce an even distribution. For a self-impinging stream pattern, oxidizer jets collide with nearby oxidizer jets. Similarly, the fuel jets collide with nearby fuel jets. For a triplet impinging stream pattern, a jet of one component is used to collide with two jets of the other component. When the volume flow rates of the oxidant and fuel are not the same, the triplet impinging stream pattern is more effective.

A shower head stream pattern injector usually employs propellant jet that does not hit and eject from the surface perpendicularly. Mixing is achieved through turbulence and diffusion processes. The engine used in the V-2 missile adopted this kind of injector. A splashed pattern injector helps propellant liquids mix; it applies the principle of a propellant jet impacting with

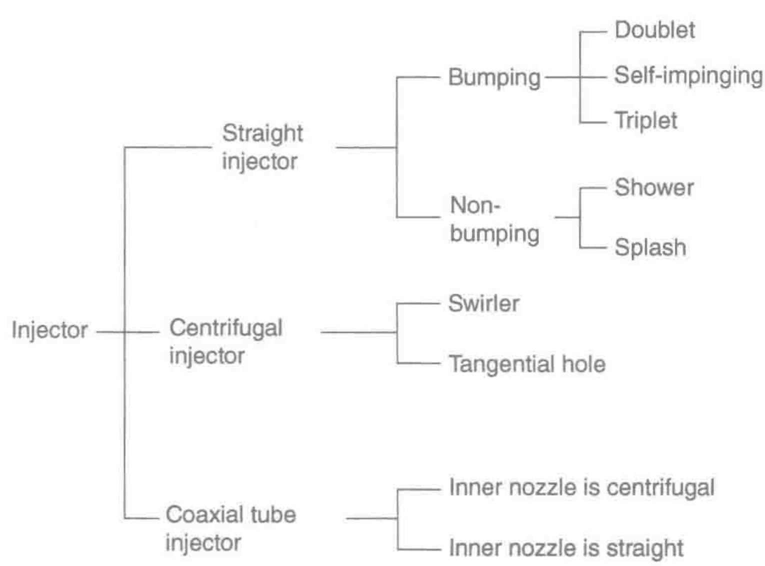

Figure 1.4 Classification of injectors.