The History of Liquid Rocket Fuel Engine

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Abstract. This paper discusses the development of liquid rocket fuel engine, fuels and fuel tanks structural design. From aerodynamic theory to experiment, both Tsiolkovsky's theoretical formula and Goddard's first test flight has made outstanding contributions. On this basis, the rocket can be truly utilized. The V-2 rockets from World War II, the various large rockets of the United States and the Soviet Union during the Cold War, as well as the modern reusable rockets, all had their different roles in different periods. In terms of fuel, the development from alcohol to kerosene to liquid oxygen and finally to liquid methane demonstrates the significance of reusable rockets in commercial spaceflight today. This is to achieve greater controllability and storage capacity. The aerospace fuel tank aims for lightweight and reusability. It features multiple layers of insulation and active cooling, and uses composite materials instead of metals to ensure the spacecraft's deep-space travel.

Keywords: Liquid Rocket Engine, Fuels and Propellants, Fuel Tanks Structural Designs, Reusable Rocket, Commercial Spaceflight.

1. Introduction

Since development of 70 years, people’s demand for communication is getting higher and higher. The status of commercial aerospace becomes extremely important for achieving global signal coverage. To save costs, the reusability of spacecraft becomes very important. This is why spacecraft has a high demand for the propulsion system. This propulsion system usually has a high specific impulse. This means that less fuel is required to achieve the same speed. In addition, the controllable thrust of spacecraft is also very important for rocket recovery. Controllable thrust enables the adjustment of the direction and magnitude of the thrust during the recovery process. Ensuring the success rate and safety of the recovery operation. The two main types of engines nowadays are the solid rocket engine and the liquid rocket engine [1]. For the control of impulse, liquid rocket engines can effectively control the direction by shutting down and restarting the engine. However, once a solid rocket engine is ignited, it will continue to operate until it runs out of fuel. The specific impulse of liquid rocket engines is usually greater than that of solid rocket engines. Comparing the advantages and disadvantages of liquid rocket engines and solid rocket engines, liquid rocket engines have a distinct advantage as a propulsion system for reusable rockets. Because they have extremely high controllability, they can be adjusted in direction to achieve recycling. Among all the aerospace companies, SpaceX stands out particularly in the use of reusable rockets. It was precisely because of the use of high specific impulse, controllable thrust and repeatable-start capabilities engines such as Merlin and Raptor, which are high-performance liquid oxygen kerosene or liquid oxygen methane engines, that SpaceX was able to launch over 8,500 Starlink satellites and achieve the accomplishment of signal coverage in multiple regions [2]. This paper will discuss the development history of liquid rocket engines, the development of fuel and propellant, the structure and design of the fuel tank and talk about the modern trends and future prospects

2. The Development History of Liquid Rocket Engines

2.1. The Early Exploration Stage (1900s-1940s)

His most influential work was "Researching the Cosmic Space Using Jet Tools", published in 1903. This was the first theoretical article to systematically expound the principles of rockets. In the article, Tsiolkovsky calculated that the speed required to enter Earth's orbit was 8 kilometers per second and proposed that a multistage rocket using liquid oxygen and liquid hydrogen as propellants could achieve this goal. He also proposed designs for thrusters used in attitude control, multi-stage ignition devices, space stations and sealed cabins, and conceived a closed ecological cycle system capable of supplying oxygen and food [3, 4]. On the theoretical basis, in September 1921, Goddard began conducting rocket experiments using liquid oxygen and gasoline. In November 1923, he successfully developed the first liquid engine, with a cylindrical combustion chamber that used high-speed airflow to atomize the liquid oxygen and gasoline mixture. On December 6, 1925, he conducted a static test in the physics laboratory of Clark University. An engine with a simple back-pressure system operated continuously on a test stand for 27 seconds and rose by its own thrust, proving for the first time that liquid-fueled rockets were feasible, and marking a crucial step for him in launching liquid rockets [5].

2.2. Warfare Catalyzes and Facilitates Practical Breakthroughs (1940s-1950s)

At the end of World War II, the Germans were eager to use long-range weapons to strike and intimidate the Allied forces in order to gain time for their survival. Among all the weapons available at that time, the one that attracted the most attention was the V-2 Rocket. V-2 Rocket is a kind of liquid rocket, The rocket is 14 meters in length and weighs 13 tons. It is powered by liquid oxygen-alcohol fuel. Its maximum range is 320 kilometers, and its speed exceeds 4.8 Mach. It is equipped with an inertial guidance system and a gas rudder control technology. It brought about destruction, yet it also pushed humanity to the brink of space for the first time, directly giving rise to the Cold War space race and the modern rocket industry [6].

2.3. The Rapid Development of Space Exploration During The Cold War Era (1950s-1990s)

After the World War II, countries embarked on a "space race", and the world witnessed a rapid development of space technology. The United States and the Soviet Union played an extremely important rule in the development of space technology. The Atlas series of launch rocket were developed by the United States. Their technical origins can be traced back to the SM-65 " Atlas " intercontinental missile, which was finalized and deployed immediately in the late 1950s. This missile initially used kerosene-liquid oxygen propellant, and this tradition has been carried forward by subsequent Atlas rocket models to the present day. The SM-65 also pioneered a unique design: during takeoff, two of the three engines were jettisoned once the fuel was exhausted, ensuring sufficient initial thrust while significantly extending the endurance of the remaining stages [7, 8]. The Saturn V launch vehicle was a heavy three-stage liquid fueled rocket specially designed by NASA for the Apollo moon landing and Skylab missions in the 1960s and 1970s. Its first stage was powered by a liquid oxygen and kerosene engine, providing approximately 3400 tons of thrust; the second stage switched to a hydrogen-oxygen engine, with a thrust of about 450 tons; and the third stage also used a hydrogen-oxygen engine, with a thrust of approximately 90 tons [9]. The RD series of rockets is a complete family of liquid rocket engines developed by "NPO Energomash" of the Soviet Union/Russia. They mainly use liquid oxygen-methane propellant. Since the 1960s, they have almost exclusively provided the core and booster power for all the country's main rockets. They are renowned for their "high-pressure afterburning, oxygen-rich staged combustion" technology: a single turbopump can flexibly drive 1, 2, or 4 thrust chambers, which is both environmentally friendly and has high specific impulse. The thrust level changes with the increase or decrease of the "number of chambers", while the core engine remains unchanged [10].

2.4. Commercial Spaceflight and The Modern Era (2000s-Now)

In the 21st century, people have been striving to reduce the cost of rocket launches. SpaceX carried out many rocket recovery experiments. In December 2015, the first stage booster of the Falcon 9 was successfully flown back to Earth and landed firmly, marking the beginning of reusable orbital rockets. The following year, it landed precisely on an offshore platform again. In March 2017, the same Falcon 9 booster was launched again and returned smoothly for the second time, becoming the first liquid-fuel rocket capable of multiple reuses. Subsequent iterations such as the Heavy Falcon, Starlink network deployment, the Crew Dragon spacecraft, and the Starship have all been developed based on the foundation laid by this recovered rocket body. Merlin and Raptor play a decisive role in the flight mission. The Merlin (liquid oxygen-kerosene) engine adopts a gas generator cycle and is designed with a focus on low cost, reusability, and mass production. To meet the requirements of vertical recovery and multiple re-flights of the carrier vehicle, this engine has the capabilities of multiple starts and deep throttling, and maintains the highest thrust-to-weight ratio among current liquid rocket engines [11]. Raptor is a new-generation full-flow staged combustion liquid oxygen-methane engine being developed by SpaceX. It serves as the sole main power for the "Super Heavy" booster and the "Starship" upper stage. The thrust of this series of engines is approximately three times that of the Merlin-1D. It can be repeatedly flown after only routine maintenance and is designed to meet the multi-mission requirements for Earth orbit, the Moon, and Mars [12].

FIG. 1 summarizes the development logic of the content above:

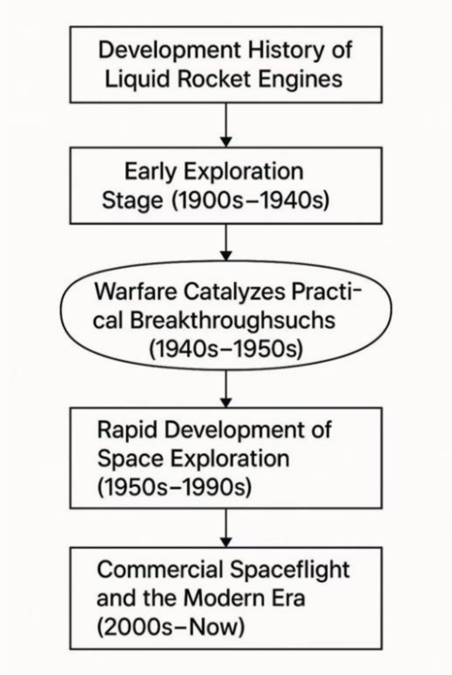

Figure 1. History about rocket development

3. Development of Fuels and Propellants

During World War II and the early post-war period, alcohol was widely used as a liquid rocket propellant due to its high heat of vaporization and also served as a regenerative coolant to prevent engine overheating. Later research found that hydrocarbon fuels could further enhance performance: they have higher density, their molecules contain no oxygen and have extremely low water content, and their energy per unit volume is superior to that of alcohol. Thus, they gradually replaced alcohol. However, regardless of which hydrocarbon fuel is chosen, it must also be capable of fulfilling the cooling task [13].

Early rockets mostly used kerosene as fuel. As the combustion time and efficiency improved, the engine structure gradually became lighter, and the thermal load increased accordingly. Pure kerosene is prone to cracking and polymerization in high-temperature cooling channels, which can lead to clogging of microchannels [14]. The decrease in cooling flow further raises the wall temperature, intensifying the polymerization and accelerating the fuel decomposition [15]. Eventually, the wall can be burned through within seconds or mechanical failure can be triggered. Even if the coolant is 100% kerosene, this vicious cycle cannot be avoided.

In the mid-1950s, RP-1, a hydrocarbon fuel with greater heat resistance, was developed and has since become the standard coolant and propellant for large liquid rockets.

In the early days of rocket theory, hydrogen was widely regarded as the ideal propellant because it had the highest specific impulse when burning with oxygen, and the only product was water, which was clean and pollution-free [16]. Under the action of 700 - 1100 °C and nickel-based catalysts, methane reacts with water vapor to produce CO and H_2. In 1998, this route accounted for approximately 95% of the global hydrogen production of about 50 billion m^3 [17]. Compared with other fuels, hydrogen has a very large volume and requires a huge storage space, which becomes the primary obstacle in engineering applications [18].

The specific impulse of liquid methane is lower than that of liquid hydrogen. However, due to its higher boiling point and density, as well as the absence of hydrogen embrittlement, it is easier to store. Moreover, compared to kerosene, it leaves less residue in the engine and is more conducive to reusability [19].

Liquid oxygen, due to its high oxygen content, high theoretical specific impulse, and compatibility with fuels such as alcohol, kerosene, liquid hydrogen, and liquid methane, has become the mainstream oxidizer for the first stage and upper stage of launch vehicles. For low thrust, early on, a high-concentration peroxide was used as an oxidizer, taking advantage of its property of catalytic decomposition and providing both gaseous oxygen and vapor thrust simultaneously. However, due to poor storage stability, it gradually faded out. In scenarios requiring long-term orbital stay and multiple launches, nitrogen tetroxide, with its liquid state at room temperature, combined with hydrazine fuels to form a storable two-component system. Although it has reliable ignition and repeated start-up capabilities, its high toxicity and corrosiveness pose significant risks to ground operations and the space environment, thus being restricted for use in manned spaceflight or unmanned satellite fields [20].

Table 1 compares the performance of the aforementioned fuels:

Table 1. The performance of aforementioned fuels

Name	Specific impulse (s)	Density (g/cm^3)	Storage temperature (K)	Reusability
alcohol	250-270	0.79	Room temperature	Decent
kerosene	270-310	0.81	Room temperature	decent
Liquid oxygen	380-450	0.07	-20	good
Liquid methane	300-380	0.42	-111	excellent

4. Fuel Tank and Structural Design

The fuel tank is a crucial component of the spacecraft's propulsion system. Its structural design directly affects the performance, payload capacity and mission reliability of the spacecraft. In the mid-20th century, spacecraft fuel tanks commonly used high-strength aluminum alloys such as 2219 and 6061, which had good weldability and mechanical properties. However, aluminum alloys have the following problems: high density, which limits the lightweighting of the structure; low-temperature brittleness, prone to cracking in low-temperature fuels such as liquid hydrogen (-253°C). high thermal conductivity, which is not conducive to the long-term storage of low-temperature fuels. Under cyclic charging and discharging pressure, the fatigue strength of the 2219 base material after 10^5 cycles was only 140 MPa, and the weld seam, due to defects such as pores and undercut, dropped to 95 MPa. The crack propagation threshold was low, far below the design margin, constituting the core failure source for repeated use [21].

In the context of the rapid evolution of reusable spacecraft technology, the material system of cryogenic propellant tanks is shifting from traditional metals to lightweight composite materials. Carbon fiber reinforced resin-based composites (CFRP) can achieve a weight reduction of 20-40% under the constraint of equal stiffness design, thanks to their mechanical advantages of 3.5 times the specific strength of 2219 aluminum alloy and 2 times that of titanium alloy. Their anisotropic characteristics and the designability of the layup enable the integration of force and heat coupling functions. Introducing nano-porous aerogel layers in the resin matrix can reduce the radial thermal conductivity to 0.15 $W \cdot m^{-1} \cdot K^{-1}$, only 1/150 of that of aluminum alloy, thereby controlling the daily evaporation rate of cryogenic propellants to below 0.05%, significantly reducing on-orbit evaporation losses. The fatigue life of CFRP under thermal-mechanical loading cycles of 77 K - 300 K exceeds 10^5 times, and the crack propagation rate is only 1/10 of that of aluminum alloy, meeting the requirements for multiple round trips of reusable spacecraft [22, 23]. Engineering practice has verified the reliability of this material: The all-composite cryogenic cabin of SpaceX Starship in the coupled test of 2.3 MPa pressure-release cycle and -183 °C liquid oxygen immersion did not show interface delamination or micro-crack penetration [24]. NASA Type III COPV uses T800/M21 prepreg winding, with a burst safety factor of 2.5, and has been used for co-storage of high-pressure helium and fuel, achieving a weight reduction of 32% while controlling the failure probability at the level of 10^{-7} [25].

The development of insulation and low-temperature storage technologies in spacecraft fuel tanks exhibits a significant duality. Although composite materials have a lower thermal conductivity, when dealing with extremely low-temperature fuels such as liquid hydrogen and liquid oxygen, they still require the collaborative effect of multi-layer insulation systems (MLI) and active thermal management technologies to achieve effective thermal control. The MLI structure consists of multiple layers of aluminum foil and spacer materials, which significantly reduces heat infiltration by minimizing the radiation heat transfer path, thereby enhancing the thermal stability of fuel storage. Foam insulation materials, such as polyurethane foam, have excellent filling properties and can adapt to complex geometries, further inhibiting heat conduction. The active cooling circulation system regulates temperature gradients through the circulation of low-temperature fluids within the cabin walls or pipes, preventing thermal stress concentration and structural deformation caused by local overheating [26]. Additionally, composite materials themselves are prone to microcracks and fuel penetration issues in low-temperature environments, so metal liners (such as titanium alloys, aluminum-lithium alloys) or nano-barrier layers need to be added to enhance sealing and structural integrity, thereby extending the fuel tank's service life [27]. However, these technical means also have obvious limitations. The MLI system has a complex structure with numerous layers, which not only increases manufacturing and assembly difficulties but also significantly increases the overall weight, undermining the advantages of lightweight design in spacecraft, foam insulation materials tend to age and become brittle under long-term low-temperature cycling and space radiation, resulting in decreased insulation performance and high maintenance costs, the active cooling system relies on precision components such as pumps, valves, and sensors, making the system complex, with high failure risks, and high energy consumption, imposing an additional burden on the spacecraft's energy system, metal liners improve the sealing ability but introduce thermal expansion coefficient mismatch problems, which may cause interface stress under temperature fluctuations, thereby increasing the risk of structural damage [28, 29]. Therefore, although insulation and low-temperature storage technologies are indispensable for ensuring fuel safety and mission reliability, the trade-off between weight, complexity, durability, and system reliability is still the key to future spacecraft design.

5. Conclusion

The liquid rocket engine has moved from theory to reality, with its demand shifting from military applications to commercial launches. The Cold War gave rise to large-thrust liquid oxygen-kerosene engines, aiming for specific impulse and reliability. Nowadays, with the rise of commercial spaceflight, low cost and reusable capabilities have become the core requirements. The development of rocket propellants has always been driven by requirements such as energy, cost, environmental protection, and reusability. In the early days, alcohol was only used for experiments. The RP-1 kerosene, which emerged during World War II, became a key component supporting the V-2 and the giant rockets during the Cold War due to its high density, high cooling, and high thrust, laying the foundation for high thrust. In the 1960s, liquid hydrogen was renowned for its high specific impulse, but it required low temperatures and large storage tanks, which was costly. In the commercial space age, with the increase in launch frequency, reusability has become the primary requirement: less carbon buildup, strong cooling, and liquid methane stood out. SpaceX's "Raptor" doubled the thrust-to-weight ratio and lifespan simultaneously, while the unit cost was reduced to one-tenth of that of a single-use engine. For the oxidizer, liquid oxygen remained dominant due to its green nature, high oxygen content, and easy availability. Highly toxic nitrogen dioxide and hydrogen peroxide gradually withdrew from the historical stage. In the future, the methane/liquid oxygen combination will continue to develop towards higher chamber pressure and fewer maintenance times, and deep space missions may bring liquid hydrogen and methane to the Moon and Mars, opening a sustainable era for interplanetary transportation. The tank is the core bottleneck for the lightweight and reusable design of liquid rockets. Traditional aluminum alloys are strong, tough and easy to weld, but the welds are prone to cracking and cannot withstand repeated take-offs and landings. After the emergence of carbon fiber composite materials, they possess the conditions of weight, low-temperature resistance, anti-fatigue, and low thermal conductivity. However, the composite materials themselves are afraid of leakage and need to be protected by metal films or nanometer barriers, combined with multiple layers of insulation, foam filling, active cooling, etc., in order to lock the extremely low-temperature propellant. Although this multi-layer protection can ensure safety, it also brings problems such as weight, complexity, and failure risks. In the future, the tank must find a better balance between materials, structure, and thermal control to achieve both lightweight and durability. Over the past century, liquid rocket engines and propellants have evolved through iterations driven by requirements such as thrust, specific impulse, cost, and reusability: the combustion chamber has shifted from gas generators to high-pressure afterburning and full-flow staged combustion, improving the thrust-to-weight ratio and controllability. The propellant has evolved along the path of alcohol - kerosene - liquid hydrogen - liquid methane, with liquid oxygen remaining the mainstream oxidizer. At the stage of the storage tank, traditional aluminum alloys, due to their excessive weight and susceptibility to fatigue, do not meet the requirements for reusability. Carbon fiber composites stand out for their light weight, low-temperature resistance, and high durability, but they also face challenges of leakage and thermal control. Multiple layers of insulation, metal liners, and active cooling solutions are employed to address these issues, bringing new contradictions in terms of weight and complexity. Integrated optimization of materials, power, fuel, structure will remain the core thread for achieving low-cost, high-frequency, and deep-space replenishable transportation.

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