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Summarization on variable liquid thrust rocket engines

YUE ChunGuo[1†], LI JinXian[2], HOU Xiao[2], FENG XiPing[2] & YANG ShuJun[3]

[1] The Second Artillery Engineering Collge, Xi'an 710025, China;
[2] National Laboratory of Combustion, Flow and Thermo-structure, Northwestern Polytechnical University, Xi'an 710072, China;
[3] 203 Institute of China North Industries Group Corporation, Xi'an 710065, China

The technology actuality and development trend of variable thrust rocket engines at home and abroad are summarized. Key technologies of developing variable thrust rocket engines are analyzed. Development advices on developing variable thrust rocket engines that are adapted to the situation of our country are brought forward.

variable thrust rocket engine, pintle injector, actuality, advice

1 Introduction

The need of control on thrust was brought forward by R.H.Goddard, one of the forerunners, who applied himself to study modern times rocket technology in the early of twenty century. The rocket engines with controlled ability of thrust have advantages in many instances of spaceflight transport and spatial mobile flight. The optimal thrust control can be achieved if variable thrust rocket engine is used by impetus equipment of spaceflight transport system and carry capacity can be made the most accordingly. If variable thrust rocket engine is used by the initiative section of manned spaceflight, over loading of astronauts can be controlled strictly and flight security of astronauts can be made sure. The agility of operation and control can be improved by variable thrust rocket engine for RAD (rendezvous and docking) and orbit maneuvering of spatial mobile aerocraft. If variable thrust rocket engine is used by missile system, maneuvering capability of flight orbit will be improved and penetration probalility of missile weapons will be enhanced consequently. In softlanding and mobile flight of the surface of non-atmosphere celestial bodies such as moon, variable thrust rocket engine is one and only impetus equipment which can be used. So many technical difficult problems need to be solved before the design and control of thrust are carried through because rocket engine is a high density release implement. Thus, the research and development of variable thrust liquid rocket engines have particular technical problems that are different from common stationary thrust[1−4].

Various techniques have been developed to achieve on-demand variable thrust control in a liquid bipropellant rocket engine, including[5]:

1) Varying the feed system pressure drop upstream of fixed injection elements (e.g., control valves);

2) Injecting gas into the liquid streams prior to injection;

3) Varying the injection element area via selectable manifolds;

4) Varying the injection element area via movable injector elements;

5) Employing capillary tubes or fluidic-like dissipation of flow pressure (e.g., vortex devices, visco-jet devices);

6) Varying the combustion chamber nozzle throat area;

7) Using multiple, independently operated combustion chambers within one integrated engine;

8) Using moderate to high rate pulse width modulation (on-off cycling) to average out to a desired equivalent

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†Corresponding author (email: wsgangzi802@qq.com)

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steady-state thrust level;

9) Combinations of two or more of the above.

Most liquid bipropellant rocket engines of today, including those used in launch vehicles, employ the first technique of using propellant feed system control valves to throttle propellants flows passing to fixed geometry injectors.

2 History, actuality and trend of foreign development

The design of injector is important especially in the design of liquid variable thrust rocket engines. Comparison of pintle injector (shown in Figure 1) with typical impinging or coaxial nozzle used in bipropellant propulsion liquid rocket engine shows that pintle injectors have particular geometrical and spray characteristics. High efficiency can be achieved by pintle injectors (96%—99%) which also have working characteristics as below: very strong throttling ability, face shut off characteristic, low cost, high reliability and operation safety. So, the researches on variable thrust rocket engines at home and abroad are mainly focused on variable thrust rocket engines using pintle injector.

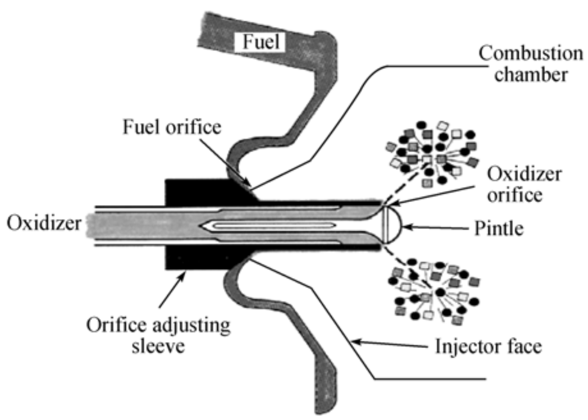

Figure 1 Principle chart of pintle injector.

For more than 40 years, more than 60 kinds of different pintle injectors have been developed by American TRW company. The application of pintle injector could date back to 1957, when the experiment was done for analyzing characteristic of the rocket propellant in Jet Propulsion Laboratory of American California Institute of Technology. However, the experiment was simple but it had topping equipment. The work was carried through by Gerry Elverum under the supervision of Art Grant. Later theoretical analysis and engineering and technical problems were accomplished by Dr. Pete Staudhammer and Jack Rupe.

Pintle injector was used for variable thrust rocket engine quickly because of its high performance and inherent combustion stability in different working conditions. In December 1961, the first pintle injector was used in rocket engine MIRA500 and its thrust change was 111.2—2224 N. It was used in rocket engine MIRA5000 again and the thrust change was 1112—22240 N. MIRA150A was also developed in 1963, with thrust change being 133.5—667 N.

In July 1963, one of the most famous variable thrust rocket engines, the lunar module descent engine, was developed by American TRW company, as shown in Figure 2. Its maximal thrust was 44.52 kN (the propellants were N_2O_4 and mixed hydrazine 50) and had 10∶1 throttling ability. The pintle-vavle mechanism orientation injector and variable cross-section cavitation venturi valve were used together by LMDE in order to ensure equal mixing ratio control in throttling range. LMDE was used successfully in Apollo 9—17 manned flight systems. At the same time, a low thrust pintle engine which included universal rocket for space applications was developed by TRW in 1966. The kind of engines used storable propellant N_2O_4/A-50 or N_2O_4/MMH, which could produce 111.6 kN or 890 N fixed thrust and use ablation or radiation cooling chamber. These engines could work in 35 Hz pulse mode and the design ignition life exceeded 10 000 s (if radiation cooling chamber was adopted). These engines were planned for applications including Gemini, Apollo, Dyna-Soar, manned space experimental station, multi-missions bipropellant propulsion system, etc.

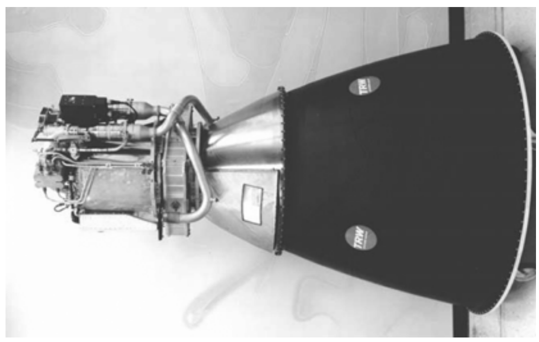

Figure 2 Lunar module descent engine of America.

A relatively simple engine which was evolved from LMDE was used on the second level of aerocrafts Delta

2914 and 3914 (from 1974 to 1978). The 44 kN fixed thrust radiation cooling engine was known as TR201 which had a 100% flight success rate (including 69 non-secret flights). The engine was very similar to the lunar module descent engine and used head/vavle components without adjustable ability. The principle of the lunar module descent engine and technical basis were also used for the development work on the variable thrust adjustable rocket engine of the NASA/TRW orbit maneuvering vehicle (OMV) plan.

Pintle injector was carried through a series of improvements by the United States from the 1980s in order to adapt it to space development and the needs of business competition. The development of sensors, control and missile technology made the intercepting destruction missile weapons possible. However, the missile needed attitude control and the late "turning", which required the rocket should have a rapid response, pulse working capability and the ability to carry out thrust linear regulation.

A pitch and yaw variable thrust rocket engine "vollenwelder", featuring high pressure, adjustable and rapid response characteristic, was developed by the United States for "sentinel" plan in 1981 (shown in Figure 3). The engine was a direct modified model of the adjustable engine used for lunar module descent engine and tactical weapon systems of TRW. It had a 19:1 thrust variable ratio, could work in steady state and pulse mode, and the pulse width of engine response in the change course of thrust was less than 8 ms. When the chamber pressure was 15.16 MPa, the engine had a relatively small size and weight. On the entire range of work, the burning efficiency could achieve 98%, working at rated thrust; the combustion efficiency could achieve 94%, working at 10 percent rated thrust; even in regulation 19∶1, the efficiency of value measured was 71%.

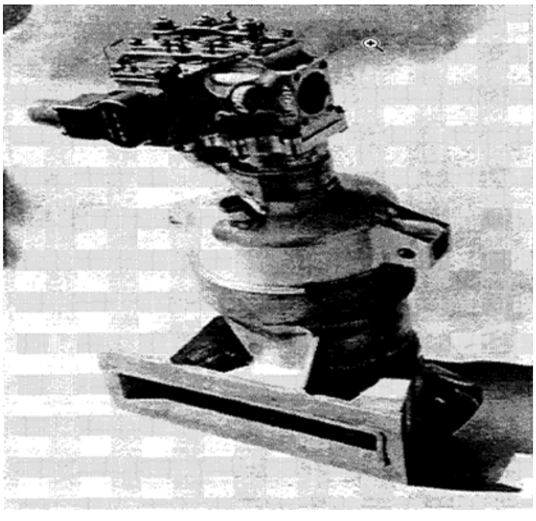

Figure 3 "Vollenwelder" variable thrust rocket engine.

Compared with other engines this engine had the following characteristics: a) realizing face shut off of pintle injector; b) propellant flux with pintle-vavle trip showed a linear change on the adjustment range of 14∶1; c) quick action valve actuators had "hard" or "soft" valve seat; d) pintle injector could control spray velocity; e) having a big thrust telescopic scope and the many types of applied propellants, but didn't produce combustion instability nor add tune cavity and partitions etc. such as restricting measures.

"Vollenwelder" adopted high pressure flux orientation pintle injector and gained a very rapid response by a quick action servo valve and a special valve actuator. In order to adapt to certain requirements of spray flow interference, a number of unique schemes were also adopted in the design of the engine including a short gap nozzle which could make exhaust airflow turn 120° and had an aspect ratio of 5∶1, and a low-cost burn corrosion lining and nozzle[2].

A simpler and realizing face shut off pintle engine (KEW) was designed for early strategic defense force energy weapons program of the Air Force and a ground test was conducted. The engine could make exhaust airflow turn 120º. It adopted N_2O_4/MMH as propellant and the working chamber pressure was 11.71 MPa. The engine could acquire 1334 N vacuum thrust and had 12 ms impulse response capacity. For exoatmospheric reentry-vehicle interceptor subsystem, TRW and Lockheed Martin Missiles Space Company signed an agreement to improve face-off pintle injector in order to provide antipersonnel weapon propellant subsystems.

Face-off injection was also successfully applied to gel propellant engine. Gel propellants have the same concentration of peanut butter. Aluminum powder or toner was used by typical gel propellant to increase the energy density of the liquid fuel (typically MMH) so that the fuel and oxidizer had very good match in temperature and flow. Gel propellant was close to the solid propellant in energy density and close to the liquid propellant in controllability. And different from solid and liquid propellants, gel propellant was applicabile broadly to military supplies of low sensitivity.

From mid-1980s to the early 1990s, another design challenge was to make small rocket engines. As part of the Air Force anti-ballistic missile plan, TRW company successfully developed a thruster that had only 22 N thrust, used N_2O_4/hydrazine as propellant and pintle injector. The radiation cooling engine ran successfully in August 1993. Its weight was only 135 g, the nozzle expansion ratio was 150∶1 and the specific impulse was greater than 3000 m/s.

In the meantime, the other improvement in design was the use of low-temperature hydrogen as fuel of pintle injector. Before, liquid oxygen or liquid fluoride oxygen as oxidant and the propellants close to normal temperature such as methane, ethane, propane, RP-1, or hydrazine as fuel were used. TRW company and Douglas and NASA Glenn Research Center worked together to prove that pintle injector could inject directly the liquid hydrogen with 28 K boiling point as a fuel and consequently the design of high performance booster engine was simplified. By the end of 1991 and forepart of 1992, a 71.2 kN thrust test engine using LOX/LH_2 was designed successfully. The engine was carried through 67 thermal tests to prove high performance of the burning, and the average combustion efficiency arrived at 97%[2].

Owing to pintle injector's alarming flexibility and the adaptability of large-scale variable working condition, pintle injectors were used much more extensively over the last decade. In the field of space propulsion, TRW completed successfully designs and identifications of the advanced LAE (liquid apogee engines) in 1996. The thrust of the engine was 472 N and the rated specific impulse was 3157.7 m/s, using N_2H_4/N_2O_4 as propellant. In August 1999, the ultimate to orbit engines TR308 LAEs for NASA Chandra spacecraft were completed, which could work in dual modes. The design of next generation LAE engine TR312 will use the chamber with rhenium material. It can produce specific impulse 3187 m/s if the N_2O_4/MMH propellant combination is used and can produce specific impulse 3236 m/s if N_2O_4/hydrazine propellant combination was used. The thrust of 57.8 and 178 kN test engine using LOX/RP-1 as propellant were also achieved successfully[6].

Statistics showed that 40% of the aircrafts costs were rocket engines. In recent years, TRW company has also developed a series of LCPEs (Low Cost Pintle Engines) such as 71.2, 111.2, 178, 1112 and 2891 kN engines in order to reduce the cost of launching spacecraft and enhance the competition of commercial launch, which all use LOX/LH_2 as propellants. The 178 kN LOX/LH_2 engine chamber pressures could be changed from 1.93 to 2.62 MPa without a combustion instability phenomenon. The TCA (Thrust Chamber Assembly) of 2891 kN thrust was proved to have good performances. Design pressure of the combustion chamber was 4.82 MPa and its burning efficiency was 96% without a combustion instability phenomenon[2].

In recent years, environmental requirements have become more and more challenging. TRW began to use non-toxic or low toxic propellants instead of the traditional toxic propellants. Recently, a thrust of 667 N pintle engine was begun to develop by Purdue University in order to determine the impact of combustion efficiency parameters, which used rocket propellant grade hydrogen peroxide and non-toxic miscible spontaneous fuels. Through the tests under the conditions of the different pintle-vavle lengths, diameters of combustion chambers and different pulses it was found that the performances had no significant change within the pore size range of the pintle-vavle and a shorter pintle-vavle would improve performances. In the pulse working condition, the total momentum had no apparent impact on performance[7].

Pintle injectors had no flight failure records for their unique structures and operation performances, nor burning instability whether the ground or in flight was found. The thrusts of 22 N—2891 kN across six orders of magnitude could be produced. The scope of chamber pressure changes was 250:1 and 25 different types of propellant combinations could be used[2]. Due to the surprising flexibility and large-scale variable status throttling ability, pintle injectors were used widely and would be further developed.

3 Domestic research actuality

The research on variable thrust engines in China began in the 1980s. In 1983[8,9], the first bipropellant variable thrust liquid rocket engine of China was tested successfully in the National Defense Scientific and Technical University and the thrusts of the engine were changed by regulating fluxes. A double-adjustable variable thrust engine was developed again by National Defense Scientific and Technical University in 1980s and the thrust of the engine was adjusted by flux adjusting cones driven by levers and pintle-vavles of the injector.

In 1992, a multiple-startup, bipropellant double-adjustable low-pressure flux orientation variable thrust liquid rocket engine, which controled the mixing ratio and spray performance synchronously, was jointly developed successfully by the Sixth Academe of the Aerospace Technology Group and National Defense Scientific and Technical University. The conventional lever system of double-adjustable variable thrust engine was used in the engine. The mixed ratio control depended on the flux adjusting vavle driven by hydraulic actuator, and the hydraulic linkage injector kept the spray velocity unchanged. Its propellant used N_2O_4/UDMH and thrust variable ratio of the engine was 5∶1.

The models and calculation procedures for analyzing response characteristic of the double-adjustable variable thrust liquid rocket engine with injectors and venturi tubes were established by Zhang[1] from National Defense Scientific and Technical University. The energy conversion and control mechanisms in the thrust chamber of the variable thrust engine were explored by Li[10] and the evaporation models of the droplets used for describing the flow field after the injecting atomization did not consider the gas chemical reaction processes.

During the Chinese Tenth Five-year's Plan, research of a new type of variable thrust engine with thrust variable ratio 10:1 was started by the Sixth Academe of the Aerospace Technology Group. The engine thrust inherited the systems and structural features of the thrust variable ratio 5:1 engine and used N_2O_4/UDMH as the propellant. Its flux regulations were realized by changing cone regulation journeys with electromagnetic valves controlled by chamber pressure feedback numerical control organs and the mixing ratio was ensured through a "T" girder connecting the two regulating cones.

4 Key technologies

In view of the research status of the liquid rocket engine thrust at home and abroad, the key technologies developing variable thrust engines are as follows.

(1) large-scale flux throttling technology

Flux and mixing ratio were adjusted by bipropellant flux control valve with adjustable cavitation venturi tube. Flux can be realized by changing throat area of venturi tube, which is achieved by adjusting the trip of venturi tube regulation cone. Precision control of mixing ratio can be realized by adjusting the relative position of the two cavitation venturi tube regulation cones and precise surface design of regulation cone.

(2) Design technology of high-performance pintle injectors

The researches on the relation of structure parameters and working parameters of pintle injector with engine performance and the relation of combustion stability with the mixing ratio of chamber wall border area should be developed. The parameters of pintle injector should be optimized in order to ensure the spray velocities of double components. On the one side, engine performance can be assured, on the other side, the security of chamber wall and throat can be insured under cooling condition in order to benefit reliability of the bodies of the engine and nozzle.

(3) Long-life, lightweight composite materials ablative body and nozzle technology

The cooling liquid film organizations will be more difficult when radiation cooling of the body is carried out in varying conditions, especially in the big variety ratio conditions. The body of the engine is very sensitive to uneven mixing ratio distributions. The current common-niobium alloy materials can not meet the requirements of variable thrust under the condition of deficient liquid film cooling. Ablative material bodies have not yet been applied to the liquid rocket engine models so far in China and their sensitivity to mixing ratio comparing with radiation cooling is lower. They have been applied widely in the United States. Ablation cooling bodies should be regarded as one of the main directions. Ablation cooling bodies and nozzles may consider composite materials in order to reduce weights.

(4) Quick response and small engine technologies

The realization of quick responses includes feedback control system, motion systems, realization of impulses, ending of the system, and many other taches. Control feedback systems may adopt a digital controller as the engine control center and the rapid control of the engine can be achieved by the optimization technologies of controlling process. The motion control of flux adjusting valves could be achieved by electromagnetic valves or small step motors and motion implements. Face-off and "zero capacity" can be achieved by pintle injectors in order to acquire the fastest start-up and shutdown responses. The miniaturization engine system can be achieved through increasing pressure of the burning chamber.

(5) Integrative numeration and analysis of combustion and flow of variable thrust engine

Models of multi-phase atomization, mixture, evaporation, combustion and flow of variable thrust engine should be established. The study on integrative numeration and analysis of combustion and flow of variable thrust engines should be developed. The influences of structural parameters and working condition parameters on the overall performance of the engine should be analyzed deeply for the optimization design of variable thrust engine to provide theoretical support.

5 Development prospect

To meet the demands of space maneuver, rendezvous, softlanding and the returns of spaceflight, the technologies of variable thrust liquid rocket engines should be developed energetically. Some preliminary recommendations are put forward as follows.

(1) Optimizing the design of pintle injector and realizing a large-scale thrust variable ratio.

(2) Breaching the technology of flux synchronous throttling of bipropellant.

(3) Capturing the key technology of composite material ablative body and nozzle and resolving the long-life of the ablation body and light-weight.

(4) Realizling high precision, fast response and miniaturization of engine.

(5) Enhancing the study on flow, combustion and heat conduction, shortening the development cycle and reducing design costs.

Variable thrust propulsion technology can be used widely in satellites, lunar probes and deep space probes, and in the future military and civilian spacecrafts it also has a wide range of applications. At the same time, variable thrust propulsion technologies may enhance the development of China’s space propulsion technologies greatly, and will breach the bottleneck of new concept propulsion technologies. High-performance propulsion with independent intellectual property rights will be formed, which may help shorten the distance from state-of-the-art technology.

1 Zhang Y L. Variable Thrust Rocket Engine and Control Technology. Beijing: National Defence Industry Press, 2001

2 Dressler G A, Bauer J M. TRW pintle engine heritage and performance characteristics. AIAA 2000-3871

3 Elverum G W. The descent engine for the lunar module. AIAA 67-521

4 Tom Mueller. TRW 40 K1bf LOX/RP-1 low cost pintle engine test results. AIAA 2000-3863

5 Gavittetc K. Testing of the 650 K1bf LOX/LH2 low cost pintle engine. AIAA 2001-3987

6 Gavittetc K. TRW LCPE 650 K1bf LOX/LH2 low test results. AIAA 2000-3853

Austin B, Heister S. Characterization of pintle engine performance for nontoxic hypergolic bipropellants. AIAA 2002-4029

7 Dressler G A. Summary of deep throttling rocket engines with emphasis on Apollo LMDE. AIAA 2006-5220

8 Xing F Y. Injector improvement design of bipropellant propulsion variable thrust rocket engine. J Propul Technol, 1990, 11(2): 43－47

9 Li X B. Combustion Efficiency Analysis of Bipropellant Propulsion Variable Thrust Rocket Engine. Changsha: National University of Defense Technology, 1984