LIQUID PROPELLANT ROCKET ENGINES

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Contents

1. Introduction

All chemical rocket engines have two common characteristics. They utilize chemical reactions in a thrust chamber to produce a high-pressure, high-temperature gas at the entrance to a converging-diverging exhaust nozzle. The hot propellant gas expands in flowing through the nozzle, and the expansion process converts a portion of the thermal energy released by the chemical reaction into kinetic energy associated with a high-velocity gaseous-exhaust jet.

2. LRE general information

The liquid propellant rocket engine (LRE) is a direct reaction engine using the liquid rocket propellant stored on a flight vehicle board for thrust creation.

The liquid rocket propellant (LRP) is a substance in the liquid state which is capable to be converted into a reactive gas jet discharging from the engine and creating a thrust as a result of the exothermal reaction associated with heat release.

LRP consists of liquid components. The propellant components can include one substance or a mixture of individual chemical substances. Each LRP component is stored in a separate tank.

At present, mono-, bi-, and multiphase propellants are employed in LRE. Bi-phase propellants consisting of the fuel and oxidizer are most often used. In this case the exothermal reaction named the burning or the oxidation reaction is the energy source.

In the case of mono-phase propellant, the catalytic decomposition reaction of some substances (for instance, hydrogen peroxide $H_2 O_2$, hydrazine N_2H_4 etc.) can be an exothermal reaction.

The burning is most widespread form of chemical energy conversion in LRE. First of all this can be explained that the great heat quantity is released during burning (8.5…12 MJ/kg).

The burning is based on the oxidation processes while the interaction between two different substances of the oxidizer and the fuel. Oxidizers concern to elements of the Periodic Chemicals Table right part (5th, 6th, 7th periods), that is fluorine, oxygen and chlorine.

Oxidizers are also chemical compounds with high content of these elements, for example nitrogen peroxide N_2O_4, hydrogen peroxide $H_2 O_2$ etc.

According to the oxidizer using kind LRE are divided into nitric acid, nitrogen peroxide, oxygenous, peroxide-hydrogenous ones etc.

The basic data of some LRE using different oxidizers are indicated in Table 1.

The LRE fuels are substances containing predominant quantity of elements oxidized during the burning reaction. These elements are situated at the first three periods of the Periodic Chemicals Table. Such elements as hydrogen, carbon, lithium, beryllium, boron, magnesium, aluminum and also compounds with a high content of these elements (for instance kerosene $C_{7,21}H_{12,29}$, methane CH_4 etc.) are main fuels.

The physical characteristics of the propellant components have important significance for engine employment. The propellant components are divided into high-temperature and low-temperature (cryogenic) ones. Under running conditions, high-temperature components have boiling temperatures above 298 K and low-temperature ones - below 120 K.

At real ambient ground conditions, high-temperature components are liquids and can be stored without losses or evaporation. For cryogenic components, in order to keep them in the liquid state, it is necessary to provide special measures, for instance, thermostatic control. Examples of the cryogenic components are oxygen, hydrogen, methane, propane, etc.

During the burning in LRE chamber, the chemical propellant energy conversion into heat takes place. This results in the gaseous combustion products (CP) conventionally with a high temperature.

After that, CP acceleration occurs into the LRE nozzle, where its heat energy is transferred into kinetic energy creating a reactive force. Thus, the main LRE unit resulting in thrust is the chamber.

Oxidizer	Fuel	Engine Mark	State	Combustion chamber pressure p_c [MPa]	Thrust in vacuum P_{vac} [kN]	Specific impulse in vacuum J_{sp} [m/s]	Mission task
1	2	3	4	5	6	7	8
F_2 Liquid	NH_3 Liquid	RD-301	Russia	11.8	98.1	3928	Upper and kick stages
O_2 Liquid	75% C_2H_5OH	RD-100	Russia	1.59	307	2325	Booster rocket R1
	92% C_2H_5OH	RD-103	Russia	2.39	500	2430	Booster rocket R5M, Geophysical rockets
	Kerosene	RD-107	Russia	5.85	1006.2	3080	Booster rocket "Vostok", First Stage
		RD-108	Russia	5.1	918	3090	Booster rocket "Vostok", Second Stage
		RD-111	Russia	5.85	1628	3110	Booster rocket "Kosmos", First Stage
		F-1	USA	7.78	7776	2982	Booster rocket "Saturn 5", First Stage
		H-1	USA	4.86	1023	2901	Booster rocket "Saturn 1 B", First Stage
		LR-105NA	USA	5.1	375	3025	Booster rocket "Atlas", Second Stage
		RD-170	Russia	24.5	8060	3295	Booster rocket "Energy", First Stage
	UDH [H_2N-$N(CH_3)$]	RD-119	Russia	7.89	105	3450	Booster rocket "Kosmos", Second Stage
	H_2 Liquid	J-2	USA	5.38	1023	4108	Booster rocket "Saturn 5", Second Stage
		RL-10	USA	2.76	66.72	4354	Booster rocket "Atlas-Zentavr", Upper Stage
		SSME	USA	20.7	2130	4464	Main Engine of "Space Shuttle"
		RD-0120	Russia	22.0	1900	4464	Booster rocket "Energy", Second Stage
		HM-7A	France	3.05	61.5	4342	Booster rocket "Arian 5", Third Stage
		LE-5	Japan	3.63	103.5	4238	Booster rocket "H1", Second Stage
N_2O_4	UDH	RD-253	Russia	14.7	1635	3100	Booster rocket "Proton", First Stage
		C5.61	Russia	9.22	18.8	3070	Engine Installation for Launching and Re-turn of Space Vehicle with Moon Ground
		11D-425	Russia	9.5-13.5	7.05-18.89	2850-3090	Correcting & Decelerating Engine Installation for Space Vehicle

		11D-426	Russia	0.91	3.09	2881	Engine Installation for Satellite Orbit Correction
		"Viking 1Y"	France	5.69	760	2900	Booster rocket "Arian 3", Second Stage
1	2	3	4	5	6	7	8
N_2O_4	MMH	R-I-E	USA	0.746	0.108	2845	Orbital Flight Control Engine "Space Shuttle"
		OMS	USA	0.863	26.68	3100	Engine Installation for Orbital Maneuvers of "Space Shuttle", Second Stage
	Aerosene-50 (50% UDH & 50% hydrazine)	LR-91-AJ-5	USA	5.7	445	3043	Booster rocket "Titan 2", Second Stage
		AJ-10-137	USA	0.7	97.5	3060	Main Engine of "Apollo" space vehicle
HNO_3 + nitrogen oxides	Kerosene	RD-219	Russia	7.30	883	2875	Booster rocket "Kosmos", Second Stage
	Amine based fuel	C5.5	Russia	6.28	45.5	2725	Deceleration Control Engine Installations
		C5.4	Russia	5.55	15.85	2610	Deceleration Control Engine Installations of "Vostok" & "Voskod" SV
	UDH	11D-414	Russia	1.18	1.98	2661	Engine Installation for Satellite Orbit Correction
H_2O_2 85/87%	Kerosene	"Gamma 8"	England	4.8	256	2457	Booster rocket "Black Arrow", First Stage

Table 1. Some LRE basic data

The scheme of bi-propellant LRE chamber is shown in Figure 1.

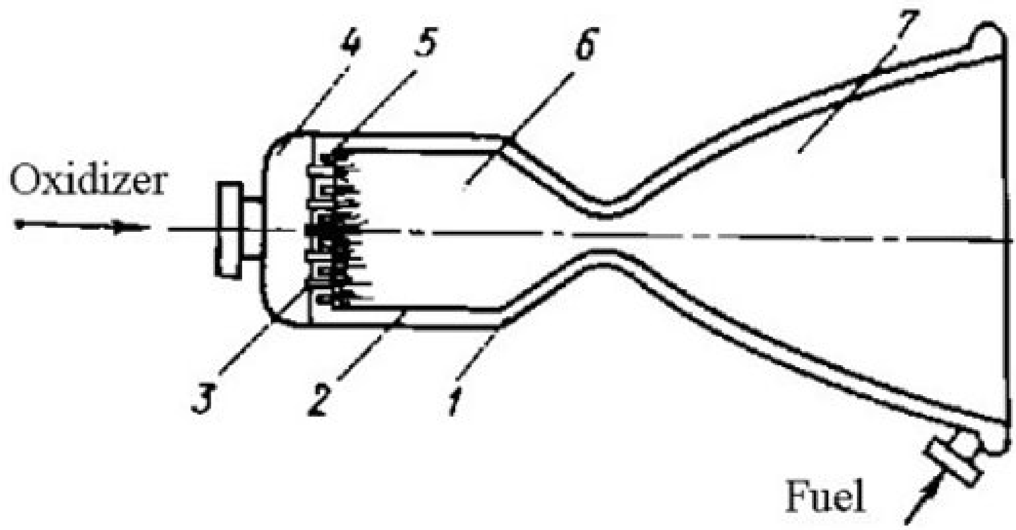

Figure 1. The scheme of bi-propellant LRE chamber

It consists of the combustion chamber (CC) 6, the nozzle 7 and is the indivisible design. CC has the injection device 4, on which special units named injectors 3 and 5 are disposed. Injectors serve for the propellant components supply into the combustion chamber.

As a rule, the chamber walls are made of two-wall construction with a gap between the inner wall 2 and the outer forced jacket 1. They are connected with each other by means of the gopher or ribs. Sometimes LRE chambers are made soldered from shaped tubes. The propellant component or components cooling LRE chamber flow through the gap or tubes.

The operating process in LRE chamber starts from components injection through the injectors under pressure. The fuel and the oxidizer are atomized into small droplets, mixed, evaporated and ignited. The propellant ignition can be carried out by chemical, pyrotechnical and electrical means. The propellant components can often be hypergolic. The ignited propellant burns under high pressure (sometimes up to 15…20 MPa and more).

During the propellant burning, gaseous CP heated up to high temperatures (3 000…4 500 K) are formed and discharge from the chamber into on environment through the nozzle. By CP motion along the nozzle, their temperature and pressure gradually decrease but the velocity is increasing exceeding the sonic speed in the nozzle throat (Figure 2). The discharge velocity in the nozzle exit reaches 2 700…4 500 m/s. As the propellant mass flow rate and the discharge velocity from the nozzle are higher then the thrust created by LRE chamber is also higher. The thrust created by the engine can change during the operation. It increases during a rocket lift off and reaches the maximum value in the airless space.

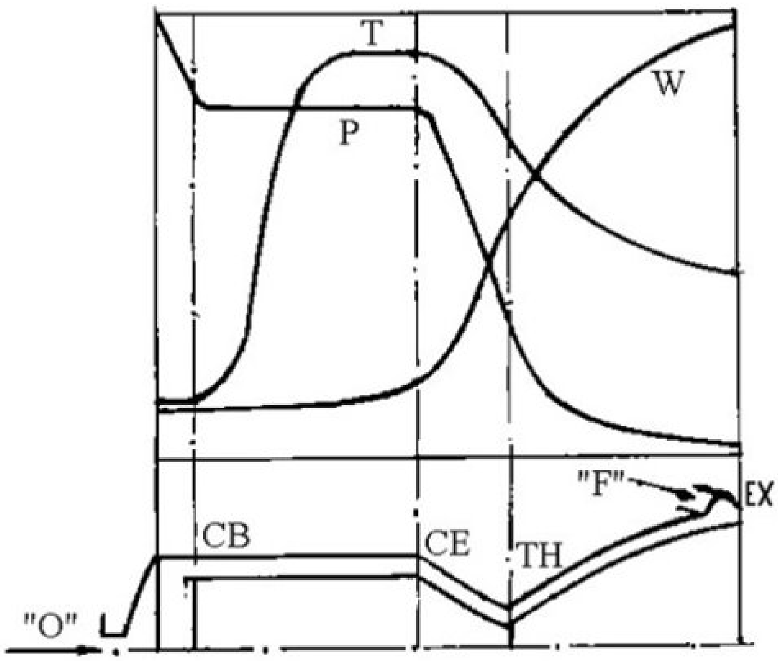

Figure 2. CP motion along the nozzle

3. Main LRE parameters

The main LRE parameters are engine thrust, total thrust impulse, specific impulse and specific mass. The engine thrust P can be expressed by the relation:

$$P = (m_p)'. W_e + F_e.(p_e + p_a) \quad (1)$$

Where m_p' is the mass flow rate of the gaseous products, W_e is the exit gas velocity, F_e is the nozzle exit area, p_e is the nozzle exit pressure and p_a is the atmospheric pressure.

The total thrust impulse I_Σ (m/s), when $P = f(\tau)$ is given by:

$$I_\Sigma = \int_0^\tau P(\tau).d\tau \quad (2)$$

If $P = f(\tau)$= const., then $I_\Sigma = P.\ \tau$.

The specific impulse (m/s) is:

$$I_{sp.m} = P/(m_f)' = W_e + [F_e.\ (p_e + p_a)]/(m_f)' = W_{ef} \quad (3)$$

The average specific impulse for the rocket engine, assuming that $P = f(\tau) =$ const.

$$I_{sp.m} = \int_0^\tau P(\tau).d\tau\ /m_f \quad (4)$$

The specific mass is defined as:

$$(M_{\text{p.p.}})' = M_{\text{p.p.}}/P \qquad (5)$$

Depending on the mission and the tactical-technical requirements for the vehicle and its control, existing LRE thrust value is varied from tenth parts to several millions of Newtons.

LRE is the main type of engines for booster rockets and space modules. It is widely used in high-altitude research rockets, long-range ballistic missiles, guided antiaircraft missiles, combat missiles of other kinds, experimental aircrafts etc.

LRE engines are divided into basic and auxiliary ones. The main or sustainer engines provide the fundamental velocity augmentation of the booster rocket (BR), the manned spacecraft (MS) or the space vehicle (SV) at their acceleration and MS or SV velocity lowering at their braking (for instance, while landing from its orbit on the Earth or for MS and SV orbit transferring).

These engines are more powerful than the auxiliary ones. For example, the space-equivalent thrust of the U.S. "Saturn V" booster rocket first stage engine (F-1 engine) is 7776 kN and the Russian "Energy" booster rocket one (RD-170 engine) has 8060 kN.

Engines for jet control systems (JCS) are auxiliary engines. These engines realize SV correction, orientation, stabilization on the orbit, their docking and other operations. These operations are generated by means of low-thrust LRE (LTLRE). These engines have a thrust ranging from parts to hundreds of Newtons. If the basic LRE operate under a continuous regime, then LRE operate in the pulse mode as a rule (see “Noise problems”, 4.4). For impulse engines, the short burning period is followed by a short shutoff period. Such cycles can reach 6 million.

Except the thrust parameter, LRE is also characterized by the efficiency (specific thrust impulse), the specific mass, the operation regime, dimensions, the combustion chamber pressure, the general arrangement and the construction of modules and units.

The specific impulse I_{sp} value is first of all dependent on the applied propellant type and gas expansion ratio into the nozzle. It increases when the chemical energy and the gas expansion ratio rise. I_{sp} influences on the rocket flight range directly. For instance, the specific impulse increment to one per cent for the intercontinental missile with 11 000 km flight range and I_{sp} = 3 040 m/s gives the range increment of five hundred kilometers.

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Bibliography

1. Vasiliev A.P., Kudryavtsev V.M., Kuznetsov V.A. et al. (1993) Fundamentals of Liquid Rocket Engines Theory and Calculation, Book 1 and 2, 383 and 384 pages, Moscow, Russia: Vystshaya Shcola (This contains thermo-gasdynamic fundamentals of operating processes in LRE chamber, the thrust theory, specific impulse, combustion process and combustion products discharge calculations, theory and calculation of different nozzles etc.).

2. Lozino-Lozinsky G.E., Bratukhin A.G. in edition (1997) Aerospace Transport Systems, book of technical papers, 416 pages, Moscow, Russia: Publishing House of MAI (The book of technical papers consists basically of the papers of leading experts of NPO "Molniya" Russian aerospace company.).

3. Sutton G.P., Ross D.M. (1976), Rocket Propulsion Elements, 327 pp., Wiley (This presents an introduction to the engineering of rockets).

Biographical Sketches

Vladimir M. Polyaev. Born in 1925, graduated from the Moscoe Aviation Institute in 1948. He took his Ph.D. degree in 1961 and became D.Sc. (Eng) in 1973. He is the author of more than 200 publications in the field of construction and characteristics of rocket engines for different applications. Research interest are concerned with energy-machine-building specifically in the area of construction and engine characteristics, thermodynamic fundamentals of operating process, thrust theory, specific impulse, combustions processes, and combustion products discharge calculations, theory and calculation of different nozzles, etc.

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