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Technical Notes

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Technical Issues Related to Propulsion Systems for Launch Vehicles

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Introduction

SPACE technology has made possible great advances in communications, weather forecasting, remote guidance, terrestrial exploration, and interplanetary probes. Many countries are involved in the development of satellites, manned space vehicles and space stations, and launch vehicles. These activities reflect the ambition of the human race to conquer space. Further progress in space technology will be largely determined by improvements in the performance, reliability, cost, and adaptability of propulsion systems.

With the notable exception of the Space Shuttle, expendable multistage rockets are used today to go into orbit and beyond. The current fleet of space vehicles is unable to meet the increasing demands of space exploration and commercialization. First, the high cost and time required for the development, manufacture, and operation of a space vehicle severely restrict the development of space activity. Second, the reliability of space vehicles is less than that of any other mode of commercial transport. Of particular importance to the propulsion community is that between 1984 and 1994 most unsuccessful launches were caused by propulsion system failures.[1] In addition to high cost and low reliability, deficiencies in launch operation, pollution, and standardization, for example, must also be overcome to realize fully the opportunities provided by access to space.

Space transport should utilize reusable hardware to minimize cost. The single-stage-to-orbit (SSTO) rocket may be best for reusability, but strict structural and propulsion requirements must first be met. Because the development process of an SSTO vehicle will be long, we can conclude that in the near term, space transportation technology will proceed along two complementary lines: the exploitation of partly or fully reusable vehicles, and the continued improvement and expansion of the existing expendable launch vehicle fleet. Success in both directions will depend on advancements made to provide higher performance, greater reliability, longer life, lower cost, and simpler operation and maintenance.

Reasonable design is the basis of reliability and economy. The design criteria should be to ultimately simplify the system, provide sufficient margin, and use a balance of inherited technology and advanced technology. Multiple-engine vehicles can rely on active redundancy, in which the failure of a single engine is overcome by operating the other engines at higher-than-nominal thrust levels. Single-engine vehicles require higher design margins, more extensive system-level tests, and pad holddown with engine shutdown capability at launch.

To enhance reliability and safety, a health-monitoring system can be used to measure and diagnose engine operation. Health monitoring also provides an opportunity to shorten maintenance time and reduce costs. The development of the health-monitoring system should be concurrent with the development of the propulsion system, at which time basic data on engine characteristics and operating parameters are obtained.

The most important technology requirements for launch vehicles are specific impulse and engine thrust-to-weight ratio, which is related to mass fraction. Specific impulse and mass fraction fundamentally characterize the performance of a rocket engine and, therefore, improvements in their values have been sought for years. The maximum specific impulse that can be obtained with a rocket engine is ultimately dependent on the propellant combination. The propellant combinations under consideration today must also meet increasingly stringent cost and environmental requirements. For a given propellant combination, improvements in combustion efficiency, engine dry weight, and system operating pressure are needed.

Combustion efficiency depends to a great extent on injector patterns, propellant physical conditions, and propellant properties. The propellants entering a combustion chamber can be generally categorized as being in one of three modes: gas/gas, gas/liquid, or liquid/liquid. The mode is determined by the power cycle employed. In theory and practice it has been shown that the combustion efficiency of injection systems that use gas/liquid propellants is higher than that of liquid/liquid injection, and that gas/gas injection offers the highest efficiency when all of the other conditions remain identical. Table 1 lists the characteristic exhaust velocity (c^*) efficiency of several engines with different injection modes and propellant combinations. It is clear that improvements in combustion efficiency should be sought, particularly for engines that use liquid/liquid propellants.

The reduction of engine dry weight, which should result in an increase in the engine thrust-to-weight ratio, has particular significance for SSTO vehicles. Table 2 lists the thrust-to-weight ratios of several representative engines. The thrust-to-weight ratios for cryogenic propellant engines are generally lower than those of storable engines, and gas-generator (GG) cycle engines

Table 1 c^* efficiency of several engines with different injection modes and propellant combinations

Engine	Injection mode	Propellant combination	c^* efficiency
F-1	Liquid/liquid	LOX/RP-1	0.943
YF-20B	Liquid/liquid	NTO/UDMH[a]	0.965
RD-170	Gas/liquid	LOX/kerosene	0.97
Space Shuttle Main Engine	Gas/liquid	LOX/H_2	0.99

[a]Nitrogen tetroxide/unsymmetrical dimethylhydrazine.

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Table 2 Thrust-to-weight ratios of rocket engines

LOX/RP-1		LOX/LH_2		NTO/UDMH or A-50	
Engine	Thrust-to-weight ratio	Engine	Thrust-to-weight ratio	Engine	Thrust-to-weight ratio
YLR105-NA-7	61.3	YF-75	29	Viking-V	97.6
LR89-NA-7	62.4	LE-5	41.2	LR-91-AJ-5	101
RD-120	75.6	HM-7B	40.8	YF-20B	106
F-1	76	RL-10-A-3-3	53.9	RD-253	130
RD-108	76.8	RD-120	57.6	LR-87-AJ-5	134
RD-170	78	LE-7	64.3	——	——
RD-180	80	Space Shuttle Main Engine	67	——	——
RD-107	89.3	J-2	67	——	——
H-1	103	HM-60	68.7	——	——

Table 3 Comparison of GG and SC cycle performance

Propellant combustion	Parameters	GG cycle	SC cycle
NTO/UDMH	Engine name	YF-20B	RD-253
	Thrust, kN	740	1470
	Chamber pressure, MPa	7.70	14.7
	Nozzle area ratio	12.69	26
	Specific impulse, s	229	285
	Mixture ratio	2.21	2.67
LOX/kerosene	Engine name	F-1	RD-170
	Thrust, kN	6770	7257
	Chamber pressure, MPa	7.78	24.5
	Nozzle area ratio	16	36.4
	Specific impulse, s	265	309
	Mixture ratio	2.27	2.6
LOX/H_2	Engine name	HM-60	LE-7
	Thrust, kN	1145	1078
	Chamber pressure, MPa	11.2	13.2
	Nozzle area ratio	45	54
	Specific impulse, s	433	449
	Mixture ratio	5.3	6

tend to have slightly higher thrust-to-weight ratios than do staged-combustion (SC) cycle engines. Increases in engine thrust-to-weight ratio can be achieved by higher system operating pressures and higher pump speeds in pump-fed systems; the use of high specific strength materials such as titanium, aluminum, magnesium and beryllium alloys, and composites; the use of advanced processing such as vacuum casting, powder metallurgy, electrobeam welding, electrosparking, and laser processing; and by a reduction in the number of parts.

Increasing system operation pressure is a useful way to increase performance, but it has practical limits. The system operating pressure is primarily determined by the type of power cycle that is used. The main types of power cycles that are used for high-pressure systems are the open GG cycle and the SC cycle. Table 3 provides performance data for a few propulsion systems that use these cycles. The upper pressure limits for the GG cycle and the SC cycle are about 15 and 25 MPa, respectively. The general trend of combustion chamber operating pressure is shown in Fig. 1.

A power balance can be used to calculate the upper pressure limit of a staged combustion cycle using liquid oxygen (LOX) and hydrogen (H_2) propellants. Using a fuel-rich preburner, and assuming turbine and pump efficiencies of 0.8, the upper operating pressure limit is about 25 Mpa. Using mixed preburners and a full-flow SC cycle, the operating pressure can exceed 30 MPa. The full-flow SC cycle has a number of other advantages that make it an attractive power cycle; including lower turbine inlet temperatures, which result in the enhancement of turbine reliability; separate oxygen and hydrogen turbopump assemblies, which mitigate tough interpropellant sealing problems, simplify development, ease maintenance, and reduce costs; and gas/gas propellant injection into the main chamber, which tends to increase combustion efficiency and the combustion stability margin.

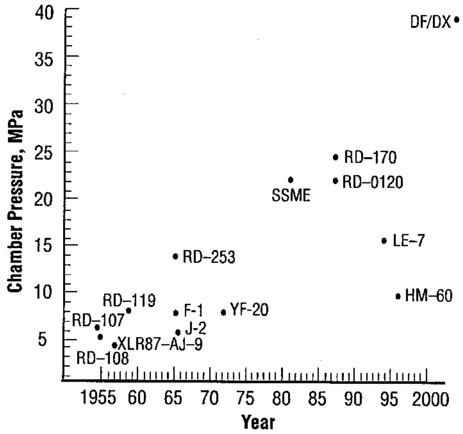

Fig. 1 General trend of combustion chamber pressure.

Pump discharge pressure and turbine power requirements increase greatly with an increase in chamber pressure. To meet the requirements for higher operating pressure, higher turbopump efficiency, and lower turbopump weight, the speed of the turbopump must increase. This presents challenges in bearing, sealing, axial loads, and rotational dynamic stability. Hydrostatic bearings are now being used to increase rotation speed, achieve lower weights and higher efficiencies, and meet the life and reliability requirements of reusability.

Thermal management requirements also become more stringent with increasing operating pressure. The combustion-chamber heat flux is almost proportional to chamber pressure. Thermal management of combustion chambers has been enhanced by improved designs and new materials. For the highest operating pressure, regeneratively cooled chambers must be used. Regenerative cooling passages today employ high aspect ratios with varying dimensions milled into zirconium–copper alloy chambers and closed out with nickel electrocast walls.

Cooling technologies under development include improved liner materials, microchannel cooling structures, elastic cooling structures, and thermal barrier coatings. The barrier layers are made of metallic or ceramic materials and can reduce heat flux by as much as 50%, but keeping the layers intact through extreme thermal cycling is a major technical challenge.[2] Transpiration cooling using platelet technology is also an attractive thermal management technique for advanced high-pressure systems.[3]

Incorporation of many of these technologies, such as an oxygen-rich preburner, staged combustion, platelet technology, hydrostatic bearings, and a stoichiometric GG design (in which the high temperature stoichiometric core gas is diluted by adding fuel or oxidizer from the chamber side wall), along with the use of a tripropellant injection scheme,[4] has led to the proposal of a dual fuel/dual expansion (DF/DX) engine concept.[5] The DF/DX engine concept can achieve combustion chamber operating pressures of 40 MPa (see Fig. 1) and engine thrust-to-weight ratios approaching 200. The DF/DX engine holds the promise of being a great innovation in liquid rocket propulsion history.

The history of space technology has shown that the status of liquid rocket engine technology is a determining factor in the development of space vehicles. While considerable progress has been made over the last five decades, a new series of technological breakthroughs are required as the state-of-the-art advances further. This paper briefly discusses a few of the major issues in liquid rocket engine development; related reports are presented in this special issue.

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