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SELECTION AND PERFORMANCE OF HYBRID PROPELLANT PROPULSION SYSTEM

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ABSTRACT:

Hybrid propulsion systems have many advantages when compared to the conventional solid or liquid propellant propulsion systems. Trials leading to eliminate the LP disadvantages, based on theoretical as well as experimental research, lead to broader HPRM applications. In order to select the suitable propellant, it is better to investigate at first such combination of propellant components that have high initial density and secures chemical reactions with the highest reactivity.

This paper discusses some typical choices for fuel and oxidizer and advantages and disadvantages of each one. Comparing the magnitude of specific impulse, various fuel-oxidizer combinations and mass-mixing ratio, burning law exponent and optimum design of the solid fuel grain, help to obtain better HP advantages. Moreover, it is not beyond possibility that further dedicated research and development of the hybrid propellants will relieve some of the inefficiency problems and therefore boost the performance figures even higher. It is anticipated that hybrids could dominate the chemical propulsion field in that century.

Nomenclature

A	Constant of fuel regression rate
A_f	Surface area of the fuel grain (m^2)
D	Combustion port diameter (m)
G_o	Oxidizer mass flux ($kg/m^2 \cdot sec$)
\dot{m}_f	Fuel mass flow rate (kg/sec)
\dot{m}_o	Oxidizer mass flow rate (kg/sec)
n	Burning exponent
O/F	Oxidizer to fuel ratio
\dot{r}	Regression rate (m/sec)

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INTRODUCTION

The primary characteristic of the hybrid rocket motor that distinguishes hybrids from solids and liquids is the non-explosively characteristic of the hybrid system. Another feature of hybrids is the relative ease with which they can be throttled. The rate of combustion of a hybrid is governed by the flow of oxidizer over the surface of the fuel, thus by throttling only the oxidizer the thrust can be modulated, that means that the termination of the oxidizer flow terminates also the HPM thrust.

Since hybrids cannot explode, they are sufficiently safe regarding their manufacture and operation. This safety translates directly into reduced development and production costs. Furthermore, since the fuel in particular is non-hazardous, it can be cast simply and thus the need for expensive, remotely - controlled casting and curing facilities are eliminated. The system is insensitive to minor grain de-bonds and cracks, because the hybrid combustion process is driven by convective heat transfer from the hot gases flowing over the grain surface. In case of a crack, the flowrate of gases over the crack is very slow so the resulting combustion occurs at a lower rate on the fuel grain surface. Thus, cracks are slowly eroded away with time, reducing the potential of a burn through to the motor case [1]. Therefore, the analysis of HP composition will be carried out and verified practically by firing tests.

HYBRID PROPELLANT SELECTION

In order to select the suitable propellant, it is better to investigate at first such combination of propellant components that has higher initial density and secures chemical reactions with the highest release of heat. The created combustion products have to be with the minimum possible molar mass to secure sufficiently high values of specific impulse. The possible states of fuel and oxidizer combinations are introduced in table 1, [2].

Table 1.

Series number	Oxidizer	Fuel
1	Gaseous	Gaseous
2	Gaseous	Liquid
3	Gaseous	Solid
4	Liquid	Gaseous
5	Liquid	Liquid
6	Liquid	Solid
7	Solid	Gaseous
8	Solid	Liquid
9	Solid	Solid

From introduced combinations of fuels and oxidizers, combinations 1, 4, 7 are useless due to gaseous fuel application. Series number 5 represents classical liquid rocket propellant. The main combinations are therefore 6, 8 and partially 9.

Usual types of the hybrid propellant are liquid oxidizer and solid fuel. Chemical agents that can be used as components of the rocket HP are substantially broad. Practically all fuels and oxidizers, forming the HP rocket at the present and future time are solid and liquid components. Possible used HP oxidizers are introduced in table 2, [3].

Table 2.

Name	Chemical formula	State	Density (Kg / m ³)
Liquid oxygen	O ₂	Liquid	1140
Fluorine	F ₂	Liquid	1510
Trifluorine	ClF ₃	Liquid	1830
98% hydrogen peroxide	98% H ₂ O ₂ , 2% H ₂ O	Liquid	1437
Nitrogen tetraoxide	N ₂ O ₄	Liquid	1450
Ammonium perchlorate	NH ₄ ClO ₄	Solid	1950
Nitrogen perchlorate	NO ₂ ClO ₄	Solid	2160
Fluorine oxide	F ₂ O	Liquid	1520
Tetranitromethane	C(NO ₂) ₄	Liquid	1620

Possible used HP fuels are introduced in table 3.

Table 3.

Name	Chemical formula	State	Density (Kg /m ³)
Polyethylene	(C ₂ H ₄) _n	Solid	940
Synthetic rubber	C _a H _b O _c N _d	Solid	1000
Lithium hydride	LiH	Solid	800
Aluminum hydride	AlH ₃	Solid	1740
Aluminum lithium hydride	AlLiH ₄	Solid	920
Beryllium hydride	BeH ₂	Solid	1600
U-symm. Dimethylhydrazine	H ₂ N ₂ (CH ₃) ₂	Liquid	790
Hydrazine	N ₂ H ₄	Liquid	1010
Pentadecane	B ₅ H ₉	Liquid	630
Liquid hydrogen	H ₂	Liquid	71

In accordance with the mentioned types of fuels and oxidizers, there exist the following groups of HP:

- ♦ 1st group - solid fuel - liquid oxidizer;
- ♦ 2nd group - solid oxidizer - liquid fuel;
- ♦ 3rd group - solid oxidizer - solid fuel;
- ♦ 4th group - three component hybrid propellants.

Presence of the 4th group is due to the fact that three component HP reaches the highest specific impulse. Mostly used HP combinations are introduced in table 4, [4].

Table 4.

Code of HP	Fuel	Oxidizer	Mass mixing ratio K_0	Exploitation feature of HP
RT-1	Carbon Hydrogen Polymer	98% H_2O_2	5.5 - 6.5	High boiling
RT-2	Lithium Aluminum Hydride	98% H_2O_2	1.08	High boiling
RT-3	Aluminum Hydride	98% H_2O_2	1.02	High boiling
RT-4	Beryllium Hydride	98% H_2O_2	1.57	High boiling
RT-5	Beryllium Hydride	N_2O_4	1.67	High boiling
RT-6	Lithium Hydride	ClF_3	5.82	High boiling
RT-7	Carbon Hydrogen Polymer	O_2	2.4	Low boiling
RT-8	Lithium Hydride	F_2	4.30	Low boiling
RT-9	Beryllium Hydride	F_2	2.11	Low boiling
RT-10	Non symmetric dimethylhydrazine	NO_2ClO_4	2.4	High boiling
RT-11	Hydrazine	NO_2ClO_4	1.12	High boiling
RT-12	Pentadecane	NO_2ClO_4	3.40	High boiling
RT-13	Aluminum Hydride	NO_2ClO_4	1.52	High boiling
RT-14	Beryllium Hydride	NO_2ClO_4	2.20	High boiling
RT-15	80% BeH_2 + 20% H_2	O_2	1.17	High boiling
RT-16	70% BeH_2 + 30% H_2	O_2	0.88	Low boiling

Thermodynamic characteristics (regardless possible losses) of above introduced HP compositions are determined for optimum ratio between components and chamber pressure four MPa are given in the table 5, [5].

Table 5.

Group	Cod of HP	Density (Kgm ⁻³)	Burning Temperature (K)	Specific impulse (Nskg ⁻¹)	Specific volumetric impulse (kNsm ⁻³)
I	RT-1	1360	3000	2570	3550
	RT-2	1140	3068	2765	3235
	RT-3	1580	3764	2882	4530
	RT-4	1500	3096	3334	5030
	RT-5	1510	3620	3235	4885
	RT-6	1530	4190	2725	4170
	RT-7	1090	3600	2745	2990
	RT-8	1290	4762	3406	4385
	RT-9	1530	4830	3688	5650
II	RT-10	1430	3466	2638	3775
	RT-11	1450	3339	2745	3982
	RT-12	1380	3950	3070	3903
III	RT-13	1800	3511	2696	4854
	RT-14	1760	3275	3070	5395
IV	RT-15	496	3507	3905	1932
	RT-16	340	2821	4150	1412

It is obvious from tables 4 and 5 that, the most acceptable is the 1st group of HP (liquid oxidizer + solid fuel). Application of hydrogen peroxide as oxidizer is reasonable in two cases, i.e. propellant RT-1 has high value of components mixing ratio $K_{opt} = 6 \div 7$. That means, $(1/6 \div 1/7)$ of the mass of propellant is located as solid grain in the combustion chamber, being stressed by high working pressure.

Majority of the propellant mass $(5/6 \div 6/7)$ is stored in loaded tank; therefore, the HP of the driving unit when RT-1 is applied can be realized with small specific mass. On the other hand, the hydrogen peroxide is mono component type of propellant. Such fact allows solving simply the task of gas generator operation needed for driving the gas turbine. Remaining HP compositions of the 1st group belong to high boiling propellants and in comparison with others they have better energetic characteristics. The disadvantage of these HP is high cost. These types are therefore recommended for upper stages of multistage rockets or cosmic vehicles. Propellants RT- 8 and RT-9 have the smallest effectiveness in case of two component types. They have very high density with respect to the specific impulse.

The HP of the 2nd group RT-10, RT-11 and RT-12 are based on prospective solid oxidizer Nitrogen Perchlorate and differ by large amount of propellant stored in the combustion chamber and small amount in the propellant tank [4].

Usual ratios of components equal to $(2.5 \div 3.5)$. So, such disadvantage is partially compensated by higher density of the nitrogen perchlorate (2600 Kg m^{-3}). Regarding the chemical activity of NO_2ClO_4 , the HP of the 2nd group reacts reliably with small delay of propellant ignition when the contact of components is secured.

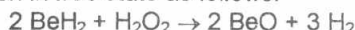
The 3rd group of the HP such RT-13 and RT-14 are propellants with different applications; RT-13 considering that it will be mastered some ways of AlH_3 synthesis and will be produced as solid blocks from them, having high density. HP produced on the base of Hydrazine (RT-14) has high price, as well as the toxicity and can be used for upper stages of multistage rockets.

The 4th group of HP - three component types and their utilization presuppose that in the combustion chamber will be located solid fuel. They have the highest calculated values of specific impulses due to the high burning temperature of solid fuels with metallic agents in oxidizer and molar mass of combustion products (due to liquid hydrogen). According to the thermodynamic calculations, the utilization of RT-15 and RT-16 for high working pressure and high expansion ratios of combustion products through the nozzle ($p_{cc} / p_A = 2000 \div 4000$) allows to raise the specific impulse until $10000 \text{ (Ns Kg}^{-1}\text{)}$ in comparison with the propellant ($\text{LOX} + \text{LH}_2$).

More complicated construction of the HPM can be expected, due to necessary introduction of the 3rd component, which has relatively low burning temperature. Unfortunately, there exist no notes about the practical applications. In addition, they are recommended for upper stages of multi stage rockets.

It is necessary to pay attention to the fact that all HPM contain sufficient amount of metals in their composition at which it is necessary to secure full burning of this metal. This can be described by the following:

HPM with propellant having the composition $\text{BeH}_2 + \text{H}_2\text{O}_2$ will have maximum specific impulse for such ratio of components, which secures full oxidation of Beryllium to BeO and creation of Hydrogen in free state as follows:



The part of Beryllium oxide in combustion products will be high (≈ 0.892). So, for such high content of the condensed phase in the HPM nozzle, combustion products are accompanied by intensive enlargement of particles. This fact can lead to about 10% drop of specific impulse [4], [6].

HYBRID PROPELLANT PERFORMANCE

Regarding the comparison of the specific impulse magnitude for various possible fuel-oxidizer combinations, the specific impulse (i_{sp}) variation with the oxidizer/fuel ratio (O/F) is illustrated by Fig. 1. Hybrid propellant rockets unlike the case of solid and liquid rockets, the O/F ratio changes over the course of a normal burn for the case of a constant oxidizer flow rate.

This is because the fuel surface area increases as the fuel burns away [7]. For a fuel grain design with a single circular combustion port the surface area will increase with diameter

$$A_F = \pi D L. \quad (1)$$

Thus for a constant fuel regression rate \dot{r} , the fuel flow rate will tend to increase with time as the diameter grows

$$\dot{m}_F = \dot{r} \rho_f A_f. \quad (2)$$

However, this increase in flow rate is counteracted by a decrease in the fuel regression rate, which is a function of mass flow rate per unit cross-sectional area. A simple theoretical expression can be used in the evaluation of the regression rate, in a hybrid propellant motor, i.e.

$$\dot{r} = A G_o^n; \quad G_o = \frac{\dot{m}_o}{\frac{\pi D^2}{4}}, \quad (3)$$

where the constant A varies with the fuel and oxidizer type, n is determined empirically (usually when using convenient regression analysis methods). The typical values of n fall between 0.5 and 0.8 . As we can see from equation (1) and equation (3) the fuel flowrate actually varies inversely to the diameter, thus the O/F ratio in case of a single circular port will increase continually throughout the burning. This shift in O/F ratio can be countered by throttling down during burning that has a good benefit of reducing the thrust as the mass is decreasing thus limiting the axial acceleration loads for the payload.

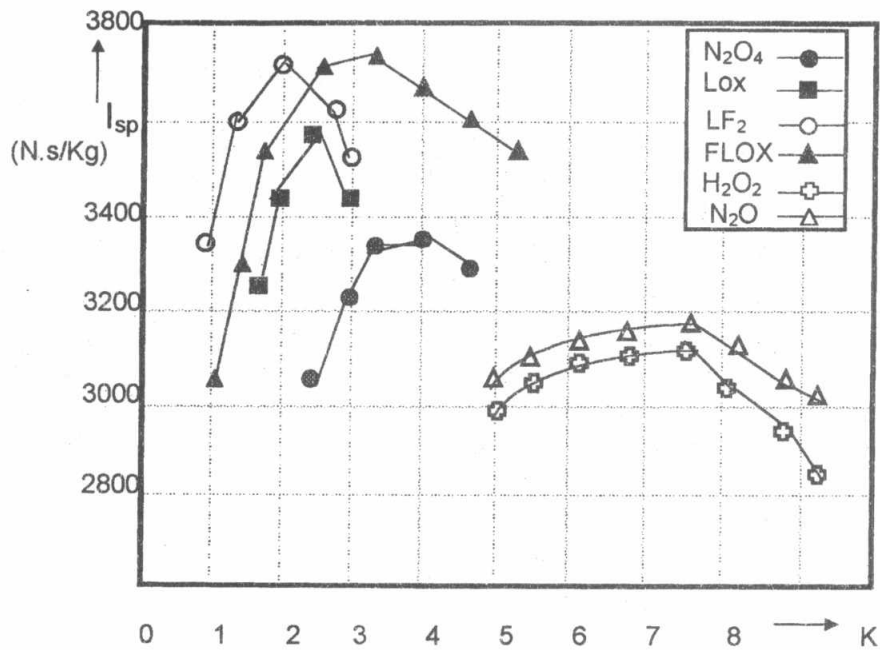


Fig. 1. Theoretical Performance of HTPB with Various Oxidizers

Using equations 1, 2, and 3 can be shown that for a certain fixed diameter D the O/F ratio shift as shown on Fig. 2 and Fig. 3 for a number of different values of n . The challenge to the hybrid motor designer is to select a fuel grain design so that the average O/F ratio is near optimum.

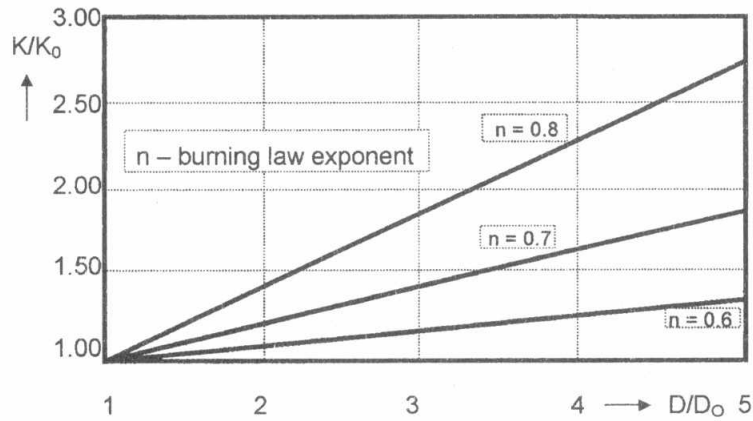


Fig. 2. Variation of O/F ratio with fuel grain diameter

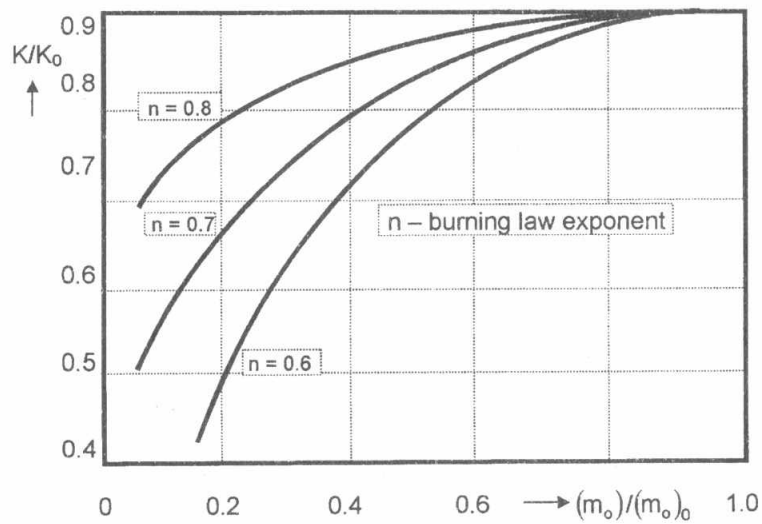


Fig. 3. Variation of O/F ratio with oxidizer mass flow rate

CONCLUSION

The paper collects important remarks about possible HP compositions, their properties, as well as advantages and disadvantages being necessary to assume for convenient HPM design as type of propulsion unit.

The proper selection of those propellants in order to meet the design goals of the propulsion system will vary assuming the mission requirements. Some of these features of different propellants have been discussed and need to be considered carefully in the design process. Having in mind the existing conditions, the verification of these theoretical approaches in the future solution will be related to HP composed from solid fuel (e.g. HTPB + additives) and gaseous oxidizer (gaseous oxygen). Such composition allows carrying out firing tests with convenient testing motor in order to contribute to the regression rate determination (as methodical approach to such solution).

Of course to construct a HP composition consisting of a liquid component and solid component from known types, the presupposed composition must fulfill the main requirements of the HPM and of course the required Tactical and Technical Requirements - (TTR) through the following:

- High initial density of the HP;
- Low burning temperature;
- Suitable working pressure;
- High specific impulse;
- HP composition must be of known and simple method of ignition (or hypergolic)
- Exhaust gases, as possible, not toxic, not smoky and with lower molecular mass.

In order to fulfill those requirements at first must be discuss the main problems facing the HP components, which are as a rule related to the rocket mission and construction.

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