AUXILIARY PROPULSION FOR HYPERSONIC VEHICLES

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Abstract

The paper discusses the subject of auxiliary solid rocket propulsion for hypersonic vehicles that are capable to reach very high altitude or even orbit. The discussion is focused on potential solid propellant combinations that can exhibit either energetic advantages (particularly significant in the upper-stage/orbital phase) or reduced environmental hazards (of major concern during the launching phase).

Introduction

Auxiliary rocket motors have been often used during the boosting stage of space launchers flight. Best known are the solid motor boosters of the US Space Shuttle. With the advent of hypersonic air-breathing vehicles that will be able to reach orbit, such as the US Aerospace Plane, the British Hotol, or the German Sänger, it is likely that auxiliary propulsion employing rocket motors will be used either in the launching phase or in the orbital portion of the trajectory or in both. In spite of the energetic superiority of liquid rocket propulsion, particularly the hydrogen-oxygen engines, solid propellant motors will be of importance due to their relative simplicity, smaller overall dimensions, and high reliability. A survey on the use of solid propellant rockets in space is given in Refs. 1 and 2. Since weight is at a premium in such applications, particularly for the upper/orbital stage phase, the use of high energy propellants is a major advantage. During the launching phase ecological aspects are expected to draw much attention in the future, leading to an extensive search to decrease the hazardous effects of the propellant combustion products.

Conducting thermochemical calculations this theoretical research will point out propellant formulations that can dramatically reduce the amount of toxic gases exhausted to the atmosphere during the launching phase. In addition a selection of extremely high performance solid propellants that may be very attractive for the orbital phase will be presented.

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Thermochemical Analysis

Energetic performance of the different propellant formulations is presented in terms of the theoretical specific impulse, I_{sp}, calculated by a thermochemical computer code [3]. Comparison between the various propellants, particularly for the initial boosting phase, is made on the basis of the standard-condition I_{sp} (expansion from 1000 psia to one atmosphere, adapted nozzle). High altitude operation is more adequately represented by the vacuum specific impulse, $I_{sp,vac}$. The $I_{sp,vac}$ calculations were made for a nozzle expansion ratio, A_e/A_t, of 60. Both equilibrium- and frozen-flow values were obtained. However, the more "conservative" frozen-flow values are believed to represent better the actual operation. Thus, frozen-flow calculations are presented in the figures, when comparing different formulations. In order to look for the optimal composition of each propellant family, the fraction of key ingredients was varied systematically.

Launching Phase

Large modern solid rocket motors often employ composite propellants based on ammonium perchlorate (AP) as the oxidizer and a polymeric binder with aluminum powder additive as the major fuel ingredients.

As a baseline for the evaluation of current high-energy solid propellants, the specific impulse of a composite propellant containing 89% solids (total of AP and Aluminum) and 11% hydrexyl-terminated polybutadiene (HTPB) binder is given as a function of the aluminum content (Fig. 1). The frozen calculations reveal peak performance of

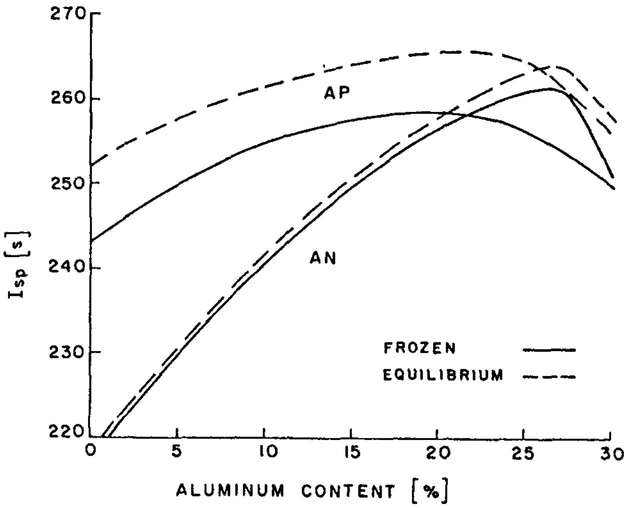

Fig. 1: Standard I_{sp} of AP and AN composite propellants containing 11% HTPB as a function of the Al content.

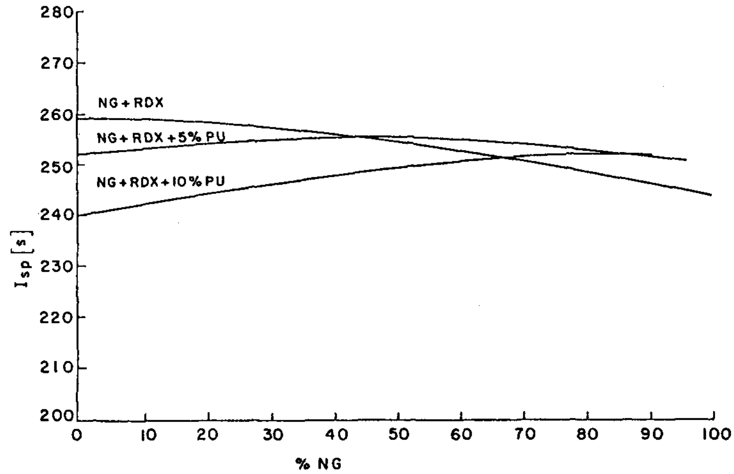

Fig. 2: Specific impulse of representative XLDB propellant formulations vs NG content.

I_{sp}=258 s for Al content of approximately 19%. Note that equilibrium expansion in the nozzle would yield maximum I_{sp} of 266 s for 22% Al.

The AP-based propellants have a major ecological drawback, as their combustion products contain large amounts of hydrochloric acid (hydrogen chloride - HCl), as high as 28%. As a most prominent example, the two 503-ton solid rocket boosters of the Space Shuttle expel to the atmosphere approximately 191 tons of HCl during their operation [4]. Because of the environmental hazards, the current AP - polybutadiene acrylic acid acrylonitrile (PBAN) terpolymer propellant combination of the Space Shuttle boosters is expected to be replaced by other formulations, which will reduce or even avoid the generation of HCl. One way to completely eliminate the HCl from the exhaust gases is by replacing the AP oxidizer by ammonium nitrate (AN). AN propellants typically have serious deficiencies such as lower I_{sp} and burning rate and poor combustion efficiency. The mere replacement of AP by AN in an HTPB propellant would yield a reduction in the specific impulse, unless very high aluminum content (in the excess of 22%) is applied (see comparison to AP-based propellants in Fig. 1). Keeping the I_{sp} high while using AN oxidizer may be accomplished by the use of high energy binders such as glycidyl-azide-polymer (GAP) plastisized with nitrate ester [4]. Another way to achieve high performance with reduced HCl hazards is to use advanced formulations, particularly those incorporating nitramine (HMX or RDX) additives [2]. The following calculations intend to indicate the energetic potential of different formulations by accounting for the main ingredients only, with no intention to point out the precise composition including the various minor additives.

Composite modified double-base (CMDB) propellants consisting of nitrocellulose (NC) and nitroglycerin (NG) with the addition of AP and a polymeric binder (e.g., polyurathane - PU) do reduce the amount of HCl generated, but do not seem to present specifically high energetic performance, although theoretically they may reach an I_{sp} of 247 s.

Formulations containing nitramines seem to be more promising. The most modern nitramine propellants are the so-called crosslinked-double-base (XLDB) propellants, where a crosslinked polymeric matrix (e.g. PU or HTPB) is mixed with double base ingredients (NC and NG) and relatively large quantities of nitramines (HMX or RDX), providing improved mechanical properties and better processability. These kinds of XLDB propellants do not produce HCl at all, yet exhibit high specific impulse. Among the typical XLDB propellant ingredients the PU or HTPB binders do not contain any appreciable amounts of oxygen, NC and RDX (or HMX) are oxygen deficient, while NG has some excess oxygen. The most energetic component is RDX (or HMX), which can yield theoretical I_{sp} of 259 s as a mono-propellant. NG has a more energetic contribution than NC in the XLDB formulation. Figure 2 presents the theoretical specific impulse of the following combinations versus NG content: NG+RDX,

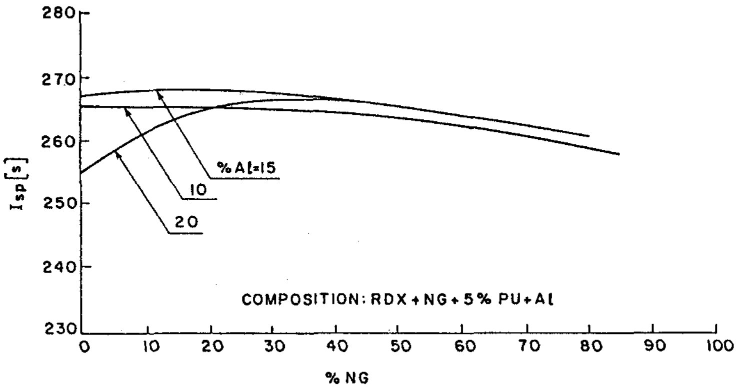

Fig. 3: Specific impulse of representative aluminized XLDB propellant formulations.

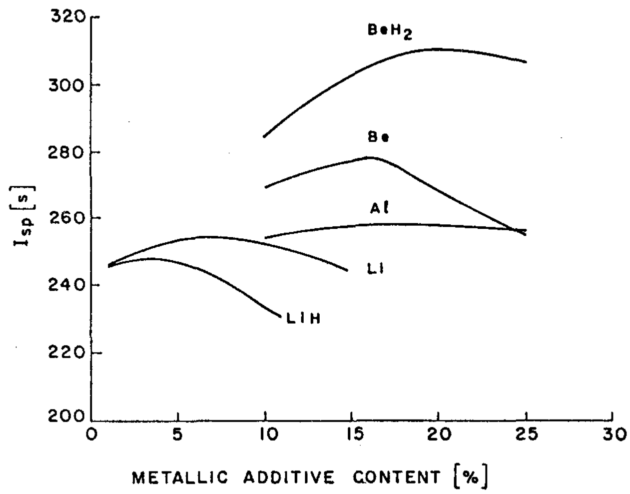

Fig. 4: Standard I_{sp} of metallized composite propellants vs metallic additive content.

NG + RDX + 5%PU, NG + RDX + 10%PU. Increasing the amount of PU causes a decrease in the peak I_{sp} which is obtained for higher NG (lower RDX) content. For no PU, maximum I_{sp} of 259 s is obtained at zero NG (100% RDX). Increasing the PU content to 5% results in a peak I_{sp} of 255 s at an NG content of approximately 40% (55% RDX). 10% PU yields an even lower peak value of I_{sp}, 252 s, which is obtained for the impractical composition of 90% NG, zero RDX. Note that increased amounts of PU cause reduction in the flame temperature.

When adding aluminum to the composition the specific impulse of XLDB propellants can be further increased, achieving a maximum higher than the peak values obtained for regular aluminized composite propellants. Figure 3 shows the theoretical I_{sp} of XLDB formulations consisting of 5% PU, NG and RDX in different amounts, and Al at 10, 15 and 20% mass fractions. The figure reveals that the optimal Al content is 15%, yielding a maximum theoretical I_{sp} value of 268 s for a composition containing 10-20% NG and 70-60% RDX, respectively. This I_{sp} value is higher by 10 seconds than the maximum I_{sp} of the HTPB-AP-Al composite propellant combinations. For a system size of the Space Shuttle solid rocket boosters, it corresponds to an approximately 38 ton saving in the total propellant mass over an HTPB-based composite propellant formulation.

High Altitude/Orbital Phase

Even air-breathing launching systems would have to use a rocket-type upper stage propulsion. Saving in the propellant mass in this stage has a direct impact on the increase of the payload mass, which means a reduction in the price per unit mass of payload. It is therefore most significant to use high energy propellants in the upper stage phase.

The limited performance of regular solid propellants compared to liquid propellants is a major disadvantage for upper stage propulsion. On the other hand, toxic hazards are less significant in this portion of the trajectory. Thus, for such applications one may consider hazardous ingredients, which cannot be used in the launching phase. Beryllium (Be) and beryllium hydride (BeH_2) are the most promising high energy additives for solid propellants.

Evaluation is performed for composite propellants consisting of 11% HTPB and total solids content (AP + metallic additive) of 89%. Five additives are considered: Al, Li, LiH, Be and BeH_2. The comparison is based on frozen flow calculations. Figure 4 compares the standard I_{sp} of the different formulations as a function of the metallic additive percentage. The figure reveals that the addition of lithium or lithium hydride to such composite propellants would result in an I_{sp} inferior to that of aluminized propellants. Beryllium and particularly beryllium-hydride-containing propellants exhibit a remarkable increase in the specific impulse. Peak I_{sp} of BeH_2 propellant attains 310 s compared to 258 s of aluminized composite propellant (20% improvement). The same trend is indicated for the vacuum I_{sp} values (expansion ratio of 60). The

Table 1: Maximum specific impulse and the corresponding metallic additive fraction for HTPB/AP/metallic addtive composite propellants containing 11% HTPB.

Metallic additive	Al	Li	LiH	Be	BeH_2
$I_{sp(f)}$ [s]	258	254	248	277	310
% additive	19.5	7	4	16	20
$I_{sp(e)}$ [s]	266	262	253	284	314
% additive	22	5	1	16	20
$I_{sp,vac(f)}$ [s]	304			333	354
% additive	18			17	19
$I_{sp,vac(e)}$ [s]	329			357	385
% additive	17			15	22

(f) denotes frozen flow
(e) denotes equilibrium flow
$I_{sp,vac}$ is calculated for nozzle expansion ratio A_e/A_t=60

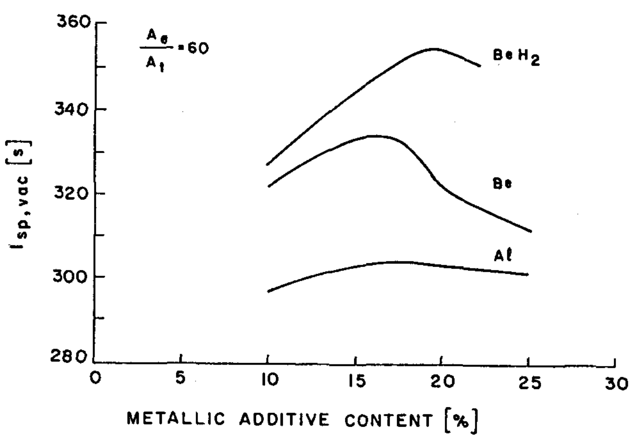

Fig. 5: $I_{sp,vac}$ of metallized composite propellants vs metallic additive content.

comparison in Fig. 5 shows an increase in the maximum I_{sp} from 304 s for Al to as high as 354 s for BeH_2. The peak I_{sp} values of the different propellants are summarized in Table 1.

Concluding Remarks

Future rocket auxiliary propulsion for hypersonic vehicles will have to give adequate solutions for both the launch and the upper stage/ orbital phases. Since a very significant aspect during launch is the environmental hazard, emphasis will be given to propellants that do not generate HCl or other toxic ingredients in the combustion products. XLDB formulations containing aluminum and large fractions of nitramines seem promising in providing relatively clean exhaust products along with increased energetic performance. For the upper stage phase, where high specific impulse is at a premium and toxic effects are of minor significance, beryllium and particularly beryllium hydride containing propellants can yield as high as 20% increase in the I_{sp} compared to modern aluminized propellants.

References

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