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THEORETICAL AND EXPERIMENTAL INVESTIGATIONS OF SOLID FUEL-RICH PROPELLANT FOR RAM ROCKET APPLICATIONS

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ABSTRACT

Five formulations of fuel-rich propellant consisting hydroxy-terminated poly-butadiene (HTPB) based polymer, ammonium perchlorate (AP) and magnesium (Mg) or aluminum (Al) as additive have been processed and investigated. Theoretical calculations of flame temperature and gas composition were determined by NASA-273 computer code. The sustained ignition / combustion of such propellant is possible with long duration pyrotechnic igniters. The experimental investigations of the effect of solid particle size range and content on fuel ballistic and mechanical properties have revealed that a considerable enhancement may be obtained with fine particle size and high content percent. High air-to-fuel ratio increases the combustion efficiency in the ramjet-mode resulting in higher specific impulse.

الخلاصة

يتناول هذا البحث تصنيع و دراسة الخصائص المقذافية و الميكانيكية لخمسة انواع من الوقود الغني المخصص لتطبيقات النفث التضاغطي. أنجزت الدراسات النظرية لهذه الأنواع الخمسة من الوقود باستخدام البرنامج المعروف (NASA-273). لقد وجد إن سرعة الاستجابة للمشاعل و استمرارية الإحتراق تعتمد على زمن تأثير المشعل البايروتكنيكي. الدراسات العملية لتأثير الحجم الحبيبي لمساحيق المواد الصلبة المضافة أثبتت انه كلما كان الحجم الحبيبي قليل و كانت نسبة المواد الصلبة عالية نحصل على مواصفات مقذافية و ميكانيكية أعلى.

أما التجارب العملية باستخدام نسبة هواء إلى وقود عالية نسبيا فقد أظهرت زيادة في كفاءة الاحتراق و بالتالي الحصول على دفع نوعي أعلى.

KEY WORDS:
Fuel-rich propellant, ramjet solid fuel.

INTRODUCTION

Due to their simplicity and reliability, solid-fuelled ramjets (SFRJ) and ram rockets (SFRR) are considered to be the least expensive air-breathing propulsion systems for supersonic flight. Mostly, (SFRR) can operate at higher thrust level but at lower specific impulse level than (SFRJ)(Benkmann,1982). The higher level of thrust realized by (SFRR) systems requires a relatively high level of fuel mass flow rate. The requirement of correspondingly high burning area or high burning rate for this large mass flow rate of fuel can be met either by enhancing the burning rate of solid fuel-propellant at the expense of the fuel percent, or by increasing the burning area at the expense of the loading density. Traditionally, the solid fuels used for ram rocket applications were metal-rich propellants (more than 50% metal content, e.g. Mg-NaNO3). The presence of large proportion of metals in the propellant matrix gives rise to metallic oxides in the product of combustion resulting in two-phase flow with attendant inefficiency in the expansion process in propulsion systems(Nair, 1998).

The present work focuses on the formulation, processing and characterization of a propellant with low percentage of metal content (about 10%). The major ingredients selected for the propellant formulations are hydroxy-terminated polybutadiene (HTPB), ammonium perchlorate (AP) and magnesium (Mg) or aluminum (Al). Extensive theoretical investigations using NASA-273 computer code(Gordon, 1971) on five combinations of the above ingredients have revealed that magnesium is favored to aluminum, as well as using fine particles of magnesium powder (less than 25) enhances both combustion and mechanical properties of the propellant. The fuel-rich propellant was processed by casting technique using commercial grade chemicals. The characterization program of the propellant includes the determination of the mechanical properties, burning rate and delivered specific impulse for both rocket-mode and ramjet-mode. An in-flight simulation set-up has been designed and erected for this purpose and described elsewhere (Zmat, 2003).

THEORETICAL INVESTIGATIONS

Propellant Formulations and Product Compositions

Five fuel compositions were formulated varying oxidizer and metal content as shown in **Table (1).**

Table (1) Fuel-rich propellant formulations

FUEL COMPOSITION	% COMPOSITION OF FUEL INGREDIENT						
	HTPB	AP	AL	Mg	TDI	Fe_2O_3	MAPO
FRP-1	70.4	25	-----	-----	4	-----	0.6
FRP-2	65.5	20	10	-----	3.9	-----	0.6
FRP-3	65.5	20	-----	10	3.9	----	0.6
FRP-4	60.4	30	5	----	3.0	1	0.6
FRP-5	60.4	30	----	6	3.0	----	0.6

These compositions were evaluated for product compositions and thermodynamics properties using NASA-273 computer code as shown in **Table (2).**

Table (2) Compositions of combustion products for the FRPs in mole fractions

FUEL COMPOSITION	CO_2	CO	N_2	H_2O	H_2	CH_4	AL_2O_3	$Mgo_{(s)}$	$C_{(S)}$	HCL
FRP-1	0.008	0.011	0.009	0.056	0.258	0.104	-------	-------	0.53	0.019
FRP-2	-------	0.018	0.009	0.001	0.411	0.011	0.019	------	0.509	0.018
FRP-3	-------	0.028	0.009	0.005	0.383	0.022	-------	0.043	0.487	0.018
FRP-4	0.002	0.024	0.009	0.019	0.354	0.049	0.010	-------	0.511	0.018
FRP-5	0.006	0.036	0.011	0.030	0.340	0.047	-------	0.023	0.48	0.023

Specific Impulse Estimations

Specific impulse in rocket-mode for the five formulations has been calculated at working pressure of (10) atmospheres using NASA-273 computer code, while the specific impulse in ramjet-mode has been determined using the below empirical formula(Sahu, 1998) at air-to-fuel ratios of (10) and (12).

$$Isp_{ram} = Isp_{roc}\ (1+\varepsilon) - (\varepsilon\, Va / g) \qquad (1)$$

Table (3) below demonstrates the calculated specific impulse for the five formulations in rocket and ramjet modes.

Table (3) Calculated specific impulse of FRPs in rocket and ramjet modes

Composition	Isp_{roc} (s)	Isp_{ram} (s) $\varepsilon=10$	Isp_{ram} (s) $\varepsilon=12$
FRP-1	125.78	526	606
FRP-2	151.31	807	938
FRP-3	145.00	738	856
FRP-4	138.11	662	767
FRP-5	137.78	658	762

EXPERIMENTAL INVESTIGATIONS

Measurements of Burning Rate

The burning rate of the five formulations was measured using either the standard test-motor firings or the Craford method. The test-motors were x-rayed before firings to make sure that there were no bubbles or cracks existed. The burning rate data have been fitted to the empirical burning rate law $r = a\, p^n$. The values of a and n obtained from the experiments for the five FRP samples are given in **Table (4).**

Table (4) a and n values for FRPs

Composition	a	n	Observations and remarks
FRP-1	---	---	Unstable combustion, a and n were not determined
FRP-2	---	---	Unstable combustion, a and n were not determined
FRP-3	0.572	0.344	Stable combustion
FRP-4	0.726	0.235	Stable combustion
FRP-5	0.707	0.302	Stable combustion

Ignitability Tests of FRPs

A pyrotechnic mixture of magnesium (24%), sodium nitrate (30%), potassium perchlorate (40%) and a binder (6%) was specifically prepared for a relatively long duration time igniter (4 seconds). The mixture was pressed in an internally insulated cylindrical tube with 7 perforations front. It was found that all formulations of the fuel-rich propellant responded to the igniter, but FRP-1 and FRP-2 suffered severe combustion instabilities. On the other hand, magnesium-based propellants showed quick response with stable combustion.

Effect of the particle size of AP on the properties of FRP-5

During the course of the present work, it has been noticed that the particle size and range of AP powder have a significant impact on the density and burning rate of the FRP. Three different particle size ranges of AP powder were used in formulating three samples of FRP-5 and both density and burning rate for the three samples were determined as shown in **Table (5).**

Table (5) Effect of AP particle size on the properties of FRP-5

Particle size range	Density (gm/cm^3)	Burning rate (mm/s)
100-140	1.003	0.526
50-60	1.135	0.842
7-11	1.254	1.562

Measurements of mechanical properties of FRPs

The mechanical properties of all formulations were determined using Instron testing machine on samples cut to ASTM standards as shown in **Table (6).**

Table (6) Mechanical properties of the FRPs

Composition	Tensile strength (Kg / cm^2)	Elongation (%)	Hardness (shore A)
FRP-1	4.925	582	13-14
FRP-2	7.0	758	13-14
FRP-3	8.2	450	19-20
FRP-4	8.9	345	30
FRP-5	9.5	350	32

Measurements of Isp of FRP-4 and FRP-5 in rocket-mode

The specific impulse in rocket mode (Isp_{roc}) of two compositions (FRP-4 and FRP-5) were determined experimentally using standard test motors. It was measured twice for each composition, and an average value was obtained to be compared with the calculated specific impulse. **Tables (7)** shows the results obtained.

Table (7) Comparison of theoretical and measured specific impulse of FRP-4 and FRP-5

composition	Theoretical Isp_{roc}(s)	Measured Isp_{roc}(s)	% difference
FRP-4	138.11	112.1	-18.8
FRP-5	137.78	119.8	-13.0

Measurements of specific impulse of FRP-5 in ramjet-mode for two different grain geometries (tubular and cigarette)

The specific impulse of FRP-5 in ramjet-mode was measured using a ramjet testing facility specifically built for this purpose. Two air-to-fuel ratios (7 and 11) were accomplished via varying the burning area of the test motor grain geometries, while the air mass flow rate was kept constant for the whole testing program. The compressed air from the testing facility was heated up to 460 K to simulate flight conditions. **Tables (8 and 9)** demonstrate the measured values of specific impulse of FRP-5 in ramjet-mode and the comparison with the theoretical values.

Table (8) Measured values of Isp_{ram} of FRP-5 in two different modes of burning

Grain type	t_b (s)	F (kgf)	m_f (kg/s)	m_a (kg/s)	m_a / m_f	Isp_{ram} (s)
Tubular	13.49	19.4	0.0468	0.337	7.2	414.5
Tubular	14.06	20.85	0.0449	0.337	7.5	464.4
Tubular	14.77	17.02	0.0427	0.337	7.9	398.6
Cigarette	19.72	19.6	0.0307	0.337	11	640.6
Cigarette	20.12	19.8	0.0318	0.337	10.6	623.6

Table (9) Average values of Isp_{ram} for tubular and cigarette grains compared to theoretical values

Grain type	Theo. Isp_{ram} (s)	Meas. Isp_{ram} (s)	Difference%
Tubular	525	426	18.8
Cigarette	700	632	9.7

Full-scale Tests

A ramjet of an antiaircraft missile (SAM-6) was chosen as a reference and tested in the absence of air (rocket-mode) at a rocket motor testing station to obtain its thrust-time curve together with video recording. The results were analyzed and compared to data available in the technical documentation of the missile. The fuel-rich propellant of the reference ramjet is a pyrotechnic type formed in cigarette shape grain by pressing technique as shown in **Fig. (1).**

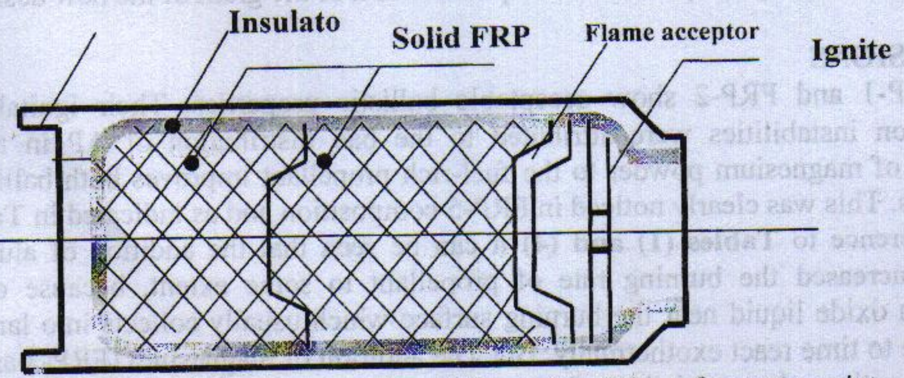

Fig. (1) Schematic representation of the grain of the reference ramjet

Starting from the obtained specifications of the reference ramjet, an alternative grain using FRP -5 composition was designed taking in consideration the difference between the burning rate of the reference propellant (29 mm / s at 17 bars) and that of FRP-5 propellant (2.5 mm / s at 20 bars). The new design is 4-points star as shown in **Fig. (2),** resulting in a decrease of 8 kg in the mass of the propellant. The alternative grain was casted in the chamber of the reference ramjet after it was emptied from the original propellant, and captively tested in the absence of air as in the reference ramjet test together with video recording. The results obtained were analyzed and compared to that of the reference ramjet as shown in **Table (10).**

Table (10) Comparison of the data obtained from captive tests of the reference and FRP-5 grains

Grain type	t_b (s)	F (N)	It (N.s)	Isp_{ram} (s)
Reference	20.44	3010	62990	92
FRP-5	19.97	3219	65520	128

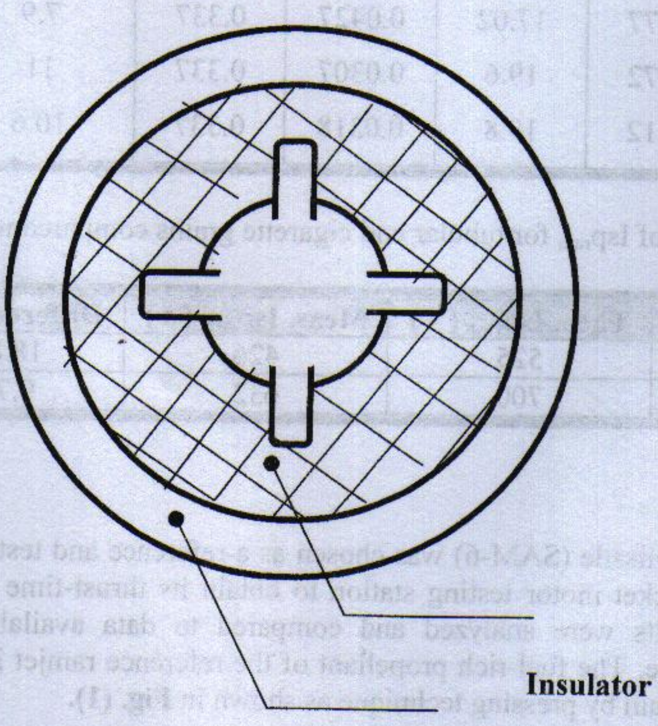

Fig. (2) Schematic representation of the grain of the new design

DISCUSSIONS

Both FRP-1 and FRP-2 show acceptable ballistic properties. Their ignitability problems and combustion instabilities were attributed to the bad distribution of AP in the polymer matrix. Addition of magnesium powder to the fuel-rich propellant improves both ballistic and mechanical properties. This was clearly noticed in FRP-5 composition and as indicated in **Tables (1) and (6).** With reference to **Tables (1) and (4)** it can be seen that the addition of aluminum (FRP-2 and FRP-4) increased the burning rate of propellant to some extent, because of the formation of aluminum oxide liquid near the burning surface which usually collects into large accumulates and from time to time react exothermally. But The addition of magnesium (FRP-3 and FRP-5) enhances the combustion characteristics of the fuel rich propellant in comparison to the addition of aluminum, because magnesium oxide loses its protective properties when the temperature exceeds 700° K and that magnesium shows a noticeable evaporation at 870° K. Furthermore the increase in AP content from 20% to 30% in the presence of aluminum is clearly reflected in better combustion stability and ease of ignition.

Table (2) clearly shows that the percentage of solid particles (Carbon particles) in the primary combustion products (rocket-mode combustion) is around 50% reflecting an acceptable energy potential in the secondary combustion stage (ramjet-mode combustion).

Table (3) gives a comparison of the specific impulse (Isp) for the rocket mode and the ramjet mode , and for the latter at different air-to-fuel ratio (ε). It can be clearly seen that Isp is higher for the ramjet mode and that increasing air-to-fuel ratio may influence the combustion stoichiometry which gives higher combustion efficiency. This was expressed as an increase in specific impulse in the ramjet mode.

Table (5) indicates that decreasing the solid particles size range (AP) enhances mechanical properties of fuel-rich propellant. Processing these fuel-rich propellants at higher percentages of solid particles (Mg) causes a considerable sedimentation of these solids during the curing time of the propellants.

Table (7) shows a comparison between calculated and experimental values of Isp for the two stable fuel formulations (FRP-4 and FRP-5). A difference of 13% and 18.8% was obtained, which is quite good.

Table (8) gives measured values of (Isp) using two different grain types of fuel element, viz, Tubular and Cigarette. Three tubular and two cigarette elements were investigated at constant air mass flow rate with the mass flow rates of gaseous products in the primary combustion of these two grain types are different resulting in different air-to-fuel ratio. It is obvious that increasing the air ratio enhances the combustion process in the secondary combustion resulting in higher Isp. This enhancement led to a reduction in the difference between the theoretical and experimental values of (Isp) and as shown in **Table (9).**

Finally, the best fuel formulation developed, here,(FRP-5) was tested against that of the standard (SAM-6) taken as reference. The result showed an improvement of about 40% was obtained in the present development as shown in **Table (10)** and is, also, indicated in **Fig.(3).**

CONCLUSIONS

A fuel propellant for ramjet application was formulated and manufactured. This propellant exhibited excellent combustion behavior as no oscillation was observed during testing.

The propellant is hydrocarbon based with magnesium as a metal additive. It gave higher specific impulse (Isp) than the Mg-$NaNO_3$ fuel-rich propellant used in SAM-6 anti-aircraft missile by about 40% in rocket mode. The magnesium powder added to enhance the propellant performance should be less than 25 micron in particle size.

Ignitability and sustaining the combustion of the developed propellant were found to be satisfactory when the (AP) percentage in its composition is around 30% and its particle size within (7-11) microns.

The test-facility experiments showed that increasing the air mass rate and fuel to air flow ratio has a significant impact on the secondary combustion of the fuel-rich propellant gases. As well as, the thermodynamic state of the rammed air (its pressure and temperature) have a direct proportional effect on the ramjet performance.

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NOMENCLATURE

F	Thrust
FRP	Fuel Rich Propellant
g	Acceleration due to gravity
Isp	Specific impulse
Isp_{ram}	Specific impulse in ramjet-mode
Isp_{roc}	Specific impulse in rocket-mode
I_t	Total Impulse
m_a	Air mass flow rate
m_f	Fuel mass flow rate
t_b	Burning time
V_a	Velocity of sound
ε	Air-to-fuel ratio