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Combustion experiments of HTPB/RFNA mixed hybrid propellants

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Abstract

A series of combustion experiments have been conducted for investigating the regression rates of mixed hybrid propellants using Red Fuming Nitrous Acid (RFNA) as liquid oxidizer and Hydroxyl-Terminated Polybutadiene (HTPB) with the addition of Ammonium Perchlorate (AP) upto 20 percent as the solid fuel. HTPB is the state-of-the-art binder used in solid propellant rocket motors and is considered to be a potential candidate fuel for hybrid rocket applications due to its higher regression rate characteristics, greater fuel value, higher carbon/hydrogen ratio and solid loading capability. One of the effective ways of increasing the regression rates in hybrids is the addition of solid oxidizer such as AP in the fuel in small percentages. This type of configuration is called “mixed hybrid” and regression rate enhancement upto 100% is obtained. A series of static tests are conducted to establish the ignition and combustion in the hybrid mode. It is seen that the hybrid propellant has burnt smoothly. The ignition pressure could also be controlled and kept to a reasonable value. Stable combustion within a variation of chamber pressure ±2% and combustion efficiency above 0.95 was achieved. The characteristics of the combustion products are calculated using the NASA CEA code. Regression rate correlations for the different combinations are obtained using the experimental data and ballistic code developed for predicting the performance of hybrid system.

Keywords: Hybrid, regression rate, mass flux, specific impulse, solid fuel, liquid oxidizer.

Nomenclature

A_t - nozzle throat area, m^2; C^*_{th} - characteristic velocity, m/s; C^*_{exp} - experimental characteristic velocity, m/s; D_{pi} - initial port diameter, mm; D_{pf} - final port diameter, mm; D_{ti} - initial throat diameter, mm; D_{tf} - final throat diameter, mm; G_o - oxidizer mass flux, kg/m^2s; m_f - mass flow rate of fuel, kg/s; m_o - mass flow rate of oxidizer, kg/s; M - molecular weight of combustion products; P_c - chamber pressure, Pa; $\dot{r}$ - regression rate, m/s; T_c - adiabatic flame temperature of combustion products, K; t_i - ignition time, sec; t_h - burn time in hybrid combustion mode, sec; O/F - oxidizer-fuel ratio; and γ - ratio of specific heats of combustion products; ξ - combustion efficiency.

Introduction

A research program has been initiated to study the combustion phenomenon in a hybrid rocket motor (HRM) using liquid oxidizers namely Red Fuming Nitric Acid (RFNA) and Nitrogen Tetroxide (N_2O_4), and Hydroxyl Terminated Polybutadiene (HTPB) with additives as fuel. A lab-scale hybrid rocket motor and test facility are realized. Though the regression rate characteristics of HTPB with a few oxidizers (such as liquid/gaseous Oxygen and Hydrogen Peroxide) are available in open literature, such data is not available for other oxidizers. The primary aim of this study is to generate data on regression rate characteristics of these oxidizer/fuel combinations. Studies are also directed to identify the oxidizer/fuel (ϕ) ratios to maximize specific impulse for these combinations, and to obtain reliable ignition and combustion over a range of oxidizer mass flux and chamber pressures.

One of the effective ways of increasing the regression rates in hybrids is the addition of solid oxidizer such as Ammonium Perchlorate (AP) in the fuel in small percentages. This type of configuration is called “mixed hybrid” and regression rate enhancement higher than 300% is reported (Frederick *et al*., 2007).

This paper details a series of hybrid combustion experiments using RFNA as liquid oxidizer and HTPB with the addition of Ammonium Perchlorate upto 20 percent as the solid fuel. These experiments have established stable combustion in the hybrid mode. The regression rate correlations for the oxidiser/fuel combinations have also been obtained.

Lab-scale rocket motor

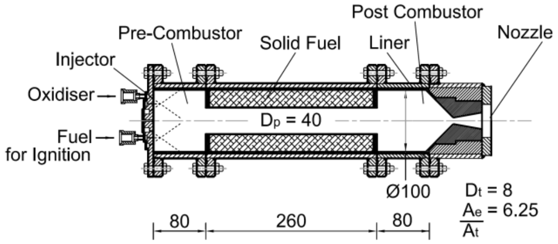
The design of the HRM is based on a ballistic code realized for predicting the performance of the motor. The code uses a zero-dimensional model to average the parameters at each instant of time. A single port cylindrical grain is assumed for the analysis. The nozzle throat diameter and oxidizer mass flow rates are held constant. The adiabatic flame temperature (T_c), molecular weight (M), and the ratio of specific heats (γ) of the combustion products are calculated using the NASA CEA (McBride & Gordon, 1996) code for equilibrium flow at every instant depending on mixture ratio, which changes during the burning time.

Using the ballistic code, performance predictions are obtained for a number of motor configuration. Based on these results, geometry of the lab-scale hybrid motor has been derived for a range of oxidizer mass flow rates and chamber pressures. Since there are no published regression rates correlations available in literature for RFNA/HTPB systems, a correlation developed for GOX/HTPB system by George and Krishnan (2001) is assumed for the preliminary design of the HRM. This is updated later with experimental results obtained from the static tests.

NASA CEA code is used to calculate the characteristics of the combustion products resulting from the combustion of liquid oxidizer RFNA with “mixed” solid HTPB fuel. The molecular formula and enthalpy of formation of the reactants are obtained from ICT Database of Thermochemical Values (Fraunhofer-Institut für Chemische Technologie Computer Code Version-3, 2001).

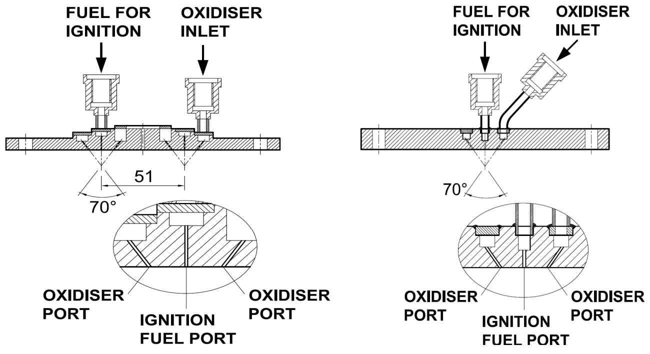
The ballistic code developed is used to arrive at the geometry of the lab-scale hybrid rocket motor. Computation is done with various grain geometries (outer diameter, port diameter and length) and different oxidizer mass flow rates to obtain regression rates for a reasonable large oxidizer mass flux. The dimensions of the pre and post combustion chambers are fixed based on the considerations detailed in literature (Wernimont & Heister, 2000). The schematic of the lab-scale hybrid rocket motor considered for experiments is shown in Fig.1.

Fig.1. Geometry of the lab-scale hybrid motor



Based on preliminary calculations, the maximum mass flow rate of oxidizer requirement for the HTPB-RFNA combination is 0.06kg/s, in order to operate in the region of stoichiometric ratio. Two types of spray injectors were designed and used for the experiments namely, four doublets (90^o apart) and a single pentode injector as shown in Fig.2. The ignition of the grain before the hybrid combustion mode is obtain using ‘G’ fuel which is hypergolic with RFNA incorporating a liquid fuel port in the injector plate.

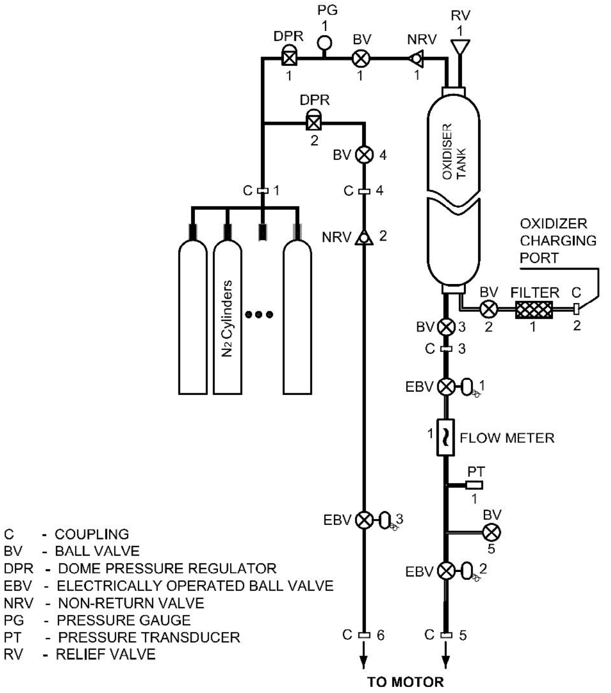
Fig.2. Injectors -Type1 and Type 2


Type-1. 4 doublets, 90^o apart *Type-2. Pentode in center*

Experimental setup

The scheme of oxidizer feed system for static test of the lab-scale hybrid rocket motor is shown in Fig.3. The oxidizer feed fluid circuit is designed to provide reliable combustion measurements with minimal complexity and redundant safety features. This system provides for safe testing of the motor by remote operation from a concrete enclosed control room. The entire fluid system utilizes materials compatible with the powerful oxidizers. The oxidizer tank is a high pressure stainless steel vessel of Ø300x 3000mm size. The maximum allowable pressure in the oxidizer tank is 100bar. A bank of Nitrogen (N_2) cylinders are used for the external pressurization of the oxidizer. A dome pressure regulator DPR-1, with pressure gage PG-1 is provided for external pressurization of the oxidizer tank. A coupling C-1 is provided for connecting the N_2 cylinders. A ball valve BV-1 is given for initiating or cutting-off the supply to the oxidizer tank. A non-return valve NRV-1 is provided aft of BV-1. One charging port with coupling C-2, a filter-1 and ball valve BV-2 is provided at the bottom of the oxidizer tank for charging the oxidizer. A relief valve RV-1 is provided at the top of oxidizer tank for pressure relief. Pressure in the oxidizer tank is recorded using pressure transducers. A ball valve BV-3 and coupling C-3 is provided for connecting to the oxidizer feed circuit of the motor.

Fig.3. Oxidizer feed system



Two electronically operated ball valves EBV-1 and EBV-2 initiate the flow of oxidizer. A flow meter-1 is provided for measuring the flow of oxidizer and this is fixed with flange joints which can be removed after the tests. The pressure transducer PT-1 measures the exit pressure aft of the flow meter. Similarly, a ball valve BV-4 and coupling C-4 is provided for connecting the nitrogen purging circuit of the motor. A ball valve BV-5 is provided before EBV-2 which is used to drain the feed lines of oxidizer after the tests. The coupling C-5 is provided to connect the feed system to the hybrid motor through a flexible line. The start-stop operation of the feed system is controlled using solenoid valves.

The ignition of the system is provided by injecting hypergolic liquid 'G' fuel along with RFNA for a small duration. The chamber pressures are measured at the head end of the pre-combustor and at two locations in the post combustor. Thrust is measured using a load cell.

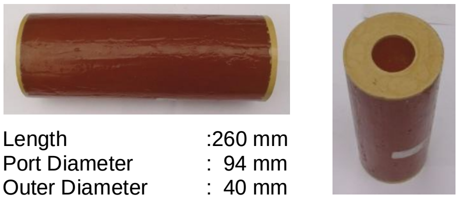
HTPB Grains

The composition of the HTPB grains developed for the tests are given in Table 1. It is seen that for HTPB with addition of 10 & 20 percent AP, the slurry should be made as viscous as possible and stirred constantly to prevent local accumulation and/or sedimentation of AP after pouring in the mould. The grains are end-inhibited with 5mm thick Epoxy as shown in Fig.4.

Table 1. Matrix of HTPB grains

Ingredient	Composition (%) w/w		
	Grain-01	Grain-02	Grain-03
HTPB	79.04	70.143	62.54
AP	0.0	10.0	20.0
Curing Agents & Catalysts	balance	balance	balance

Fig.4. HTPB grain



Length :260 mm
Port Diameter : 94 mm
Outer Diameter : 40 mm

Experimental results

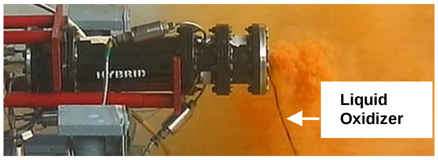
Initial Tests

Tests were conducted to establish the ignition process followed by hybrid combustion. In the first case, an oxidizer flow rate of ~75gm/sec was considered for test and RFNA was injected for ~5.0sec before ignition. The initial flow of RFNA before ignition led to accumulation of oxidizer in the pre-combustor and the flooding of the motor, This resulted in a very weak combustion in hybrid mode due to excess oxidizer present and chamber pressure of ~2.0bar was obtained (Fig.5).

Fig.5. Test-01 of HTPB with 10%AP and RFNA

From the above observations, it was decided to start ignition simultaneously with the injection of the liquid oxidizer. The configuration of the pre-combustor was modified for direct injection of oxidizer into the solid fuel port. However, hybrid combustion could not be established with the given modification. It was observed that the liquid oxidizer flowed out of the nozzle as shown in Fig.6.

Fig.6. Test-02 of HTPB with 10%AP and RFNA



The test established the fact that a re-circulation zone for hot gases is essential ahead of the solid fuel even for the liquid oxidizer spray.

Tests of HTPB with 20%AP and RFNA

Based on the experience of the initial two tests, the nozzle was changed with throat diameter and area ratio of 8.0mm and 6.25 respectively, to increase the chamber pressure. The grain-03 with 20% AP content in the fuel was considered in the next test (1A) with a flow rate of ~35gm/sec. The nozzle was modified with throat diameter of 8.0mm and area ratio 6.25 in order to increase the chamber pressure.

The ignition was initiated with the simultaneous injection of RFNA and 'G' fuel for ~4.0 sec. Ignition time was increased as the oxidizer flow rate has been reduced. The motor functioned well in the hybrid mode for 18.3sec till the oxidizer was switched OFF. The exit flame was observed to be stable indicating efficient hybrid combustion (Fig.7). An average chamber pressure of 14.5bar and thrust of ~8.5kgf were measured. It is seen that the combustion is stable and the small perturbations in pressure is well within limits of ±2%.

Fig.7. Static test of HTPB with 20%AP and RFNA

The total mass of oxidizer used in hybrid mode is obtained by integrating the measured mass flow rate of the oxidizer during the hybrid combustion mode (Eq.1).

$$m_o(tot) = \int \dot{m}_o dt \qquad (1)$$

The mass of fuel consumed, m_f(tot) through weight and volume measurements compares within 2-3% accuracy. The average O/F ratio during the operation of the hybrid motor is ~1.2 and the theoretical characteristics velocity C^*_{th} is obtained from CEA code (Eq.2).

$$O/F_{(avg)} = \frac{m_o(tot)}{m_f(tot)} \quad (2)$$

The characteristics velocity C^*_{exp} from experiment is obtained from the static test firing in hybrid operation based on Eq.3 and the combustion efficiency factor ξ of 0.83 is obtained (Eq.4).

$$C^*_{exp} = \frac{\int (P_c x A_t) dt}{m_o(tot) + m_f(tot)} \quad (3)$$

$$\xi = \frac{C^*_{exp}}{C^*_{th}} \quad (4)$$

Using the experimentally obtained value of ξ, the ballistic code is used to arrive at a regression rate correlation by matching experimentally measured chamber pressure, thrust, oxidiser flow rate and fuel consumed. The drop in chamber pressure due to nozzle throat erosion is considered by measuring the throat diameter after test and factoring this effect in the code.

The test was repeated (2A) for the same grain with a pentode injector for an average oxidizer flow rate of 75 gm/sec. The test conditions for the two tests of HTPB with 20%AP and RFNA are given in Table 2. The port diameter variation over a length of 250mm is around ±3mm after the test and a typical measurement of the port diameter axially at four angular orientations (90^o apart) is shown in Fig.8(a).

The port diameter of two motors after static firing is shown in Fig.8(b). The chamber pressure and thrust time traces for the above tests are shown in Figs.9&10 respectively. The actual oxidizer flow rates in the tests have been used in the ballistic code for the regression rate correlation and prediction.

Table 2. Test details for HTPB with 20%AP and RFNA

Test	t_i	t_h	$\dot{m}_o$	D_{ti}	D_{tf}	D_{pi}	D_{pf}
1A	4.0	18.3	38.0	8.2	8.4	40.0	64.0
2A	2.3	17.2	83.5	10.05	11.63	64.0	85.0

Fig.8(a). Port diameter along length after static test

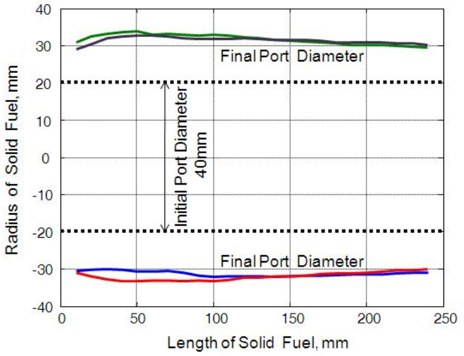


Fig.8(b). Port diameter after static tests

Fig.9. P_c vs time for HTPB with 20%AP and RFNA

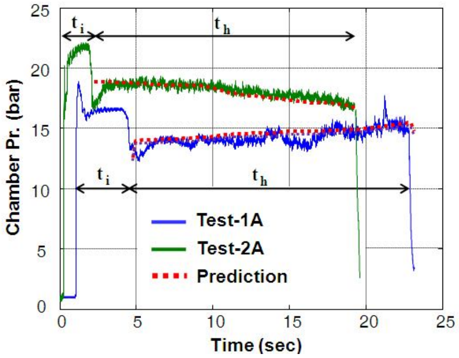
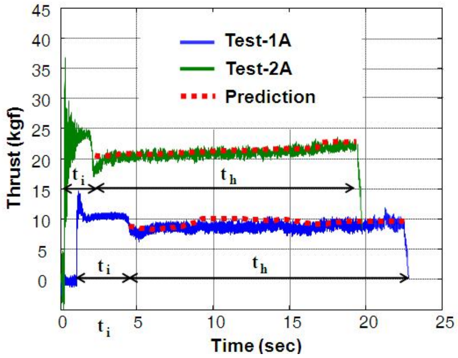


Fig.10. Thrust vs time for HTPB with 20%AP and RFNA



A combustion efficiency factor between 0.84-0.86 was obtained with specific impulse near 160 and 180sec for the two tests. The variation of oxidizer mass flux calculated for the tests 1A & 2A is between 27.0 to 12.0kg/m^{2}s. A new regression rate correlation for HTPB fuel having 20%AP content in combination with RFNA as oxidizer is obtained from the tests and is given in Eq.5.

$$\dot{r} = 7.8 \times 10^{-5} G_{ox}^{0.64} D_p^{-0.11} \quad (5)$$

Tests of HTPB (without AP) and RFNA

The following factors were considered for arriving at the oxidizer flow rate for this combination, namely 1) the assumption that the regression rate for this combination will be less than half in comparison with grain-03 having 20%AP and 2) the oxidizer flow rate should be increased to operate near to the stoichiometric O/F value (~4.9). Accordingly, an oxidizer flow rate of ~55gm/sec was considered for the test.

For test-1B, the ignition time was kept almost same as for that of test-1A. The motor functioned well in the hybrid mode for ~23.5sec till the oxidizer was switched OFF.

The small perturbations in pressure are well within the limits of ±2%. The exit flame was stable indicating efficient hybrid combustion shown in Fig.11. Throat erosion started after ~17.0sec and is seen from the constant drop in chamber pressure. The throat diameter increased from 8.4 to 9.65mm after the test, due to throat erosion.

Fig.11. Static test of HTPB and RFNA

The port diameter variation is within ±3mm after the test and the mass of fuel through weight and volume measurements compares within 2-3% accuracy. The average O/F ratio during the operation of the hybrid motor is ~4.6.

The test (2B) was repeated for the same grain with a pentode injector for an average oxidizer flow rate of 84 gm/sec. The test conditions for the two tests of HTPB and RFNA are given in Table 3. The chamber pressure and thrust time traces for the above tests and comparison with the prediction are shown in Figs12&13 respectively.

Table 3. Test details for HTPB and RFNA

Test	t_i	t_h	$\dot{m}_o$	D_{ti}	D_{tf}	D_{pi}	D_{pf}
1B	3.5	23.5	58.0	8.4	9.65	40.0	57.6
2B	2.1	10.2	83.5	8.0	9.34	57.6	65.7

Fig.12. P_c vs time for HTPB (without AP) and RFNA

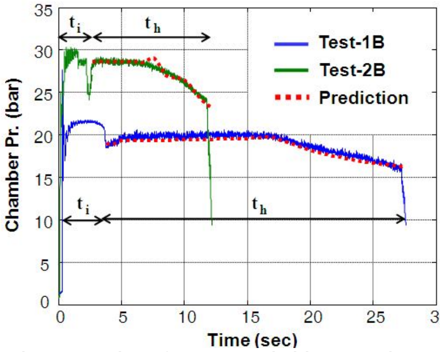
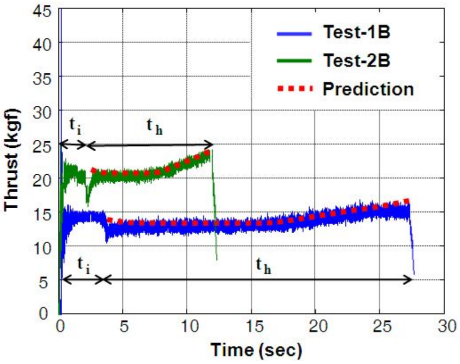


Fig13. Thrust vs time for HTPB (without AP) and RFNA



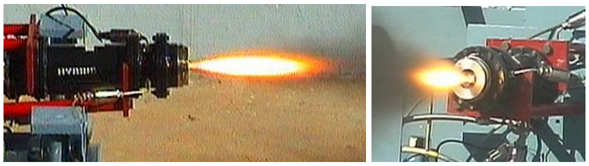
A combustion efficiency factor between 0.93-0.95 has been achieved and the specific impulse is in the range of 200-215sec for the two tests. The variation of oxidizer mass flux calculated for the two tests 1B & 2B is between 45.0 to 23.0kg/m^{2}s. A new regression rate correlation for pure HTPB fuel in combination with RFNA as oxidizer has been obtained from the tests and is given below:

$$\dot{r} = 5.9\times 10^{-5}\, G_{ox}^{0.44}\, D_p^{-0.11} \qquad (6)$$

Tests of HTPB with 10%AP and RFNA

A new grain-02 with 10%AP content in the fuel was considered in the test (1C) with a flow rate of ~62gm/sec. The nozzle throat was modified by introducing a Tungsten-Copper insert to avoid throat erosion. The ignition time was kept around 2.0sec. The motor functioned well in the hybrid mode for ~15.5sec till the oxidizer was switched OFF (Fig.14).

Fig.14. Static test of HTPB with 10%AP and RFNA



The port diameter variation is within ±3mm after the test and the mass of fuel through weight and volume measurements compares within 2-3% accuracy. The average O/F ratio during the operation of the hybrid motor is ~3.8.

The test (2C) was repeated for the same grain with a pentode injector for an average oxidizer flow rate of 76 gm/sec. The test conditions for the two tests of HTPB with 10%AP and RFNA are given in Table 4. The chamber pressure and thrust time traces for the tests are shown in Figs.15&16 respectively.

Table 4. Test details for HTPB with 10% AP and RFNA

Test	t_i	t_h	$\dot{m}_o$	D_{ti}	D_{tf}	D_{pi}	D_{pf}
1C	1.9	15.4	62.0	8.1	8.1	40.0	57.0
2C	1.8	17.5	76.0	8.1	8.15	57.0	72.6

Fig.15. P_c vs time for HTPB with10%AP and RFNA

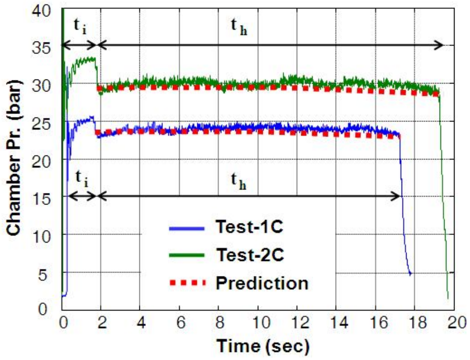
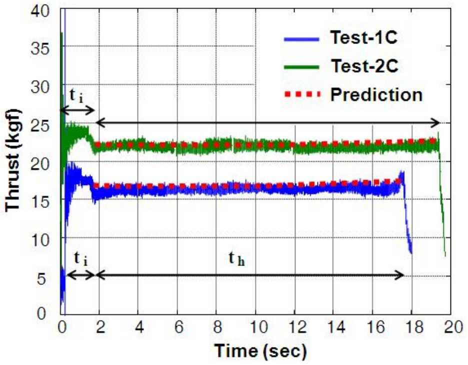


Fig.16. Thrust vs time for HTPB with 10%AP and RFNA



The variation of oxidizer mass flux calculated for the above two tests (1C & 2C) is between 47.0 to 18.5kg/m^{2}s. A regression rate correlation for HTPB with 10%AP fuel and RFNA as oxidizer has been obtained from the tests and is given in Eq.7.

$$\dot{r} = 6.4 \times 10^{-5} G_{ox}^{0.51} D_p^{-0.12} \qquad (7)$$

Conclusions

Hybrid motor experiments were conducted for RFNA as liquid oxidizer and solid fuel namely HTPB with and without the addition of AP up to 20%. The design of a lab-scale HRM was based on a ballistic code developed with regression rate assumed from literature. An experimental setup for conducting the static tests of the motor was realized.

A set of hybrid experiments were conducted with RFNA as oxidizer and solid fuel HTPB with addition of 0, 10 and 20 percent AP. Initial tests establish the ignition process and correct ignition parameters to obtain stable hybrid combustion were evolved. The ignition pressure could also be controlled and kept to a reasonable value. Stable combustion within a variation of chamber pressure ±2% and combustion efficiency of up to 0.95 was achieved. The port diameter is nearly constant throughout the length of the fuel grain after the tests indicating smooth regression rate of the solid fuel.

The regression rate correlations obtained from the present experiments revealed that the HTPB fuel with 20%AP has higher regression rate, which in this case is more than double that of the pure HTPB fuel. New regression rate correlations for liquid oxidizer RFNA with solid HTPB fuel having 0, 10% and 20% AP were derived from the experiments. Performance predictions indicated that the specific impulse is in the range of 215s when the hybrid system was operated near the stoichiometric value. The I_{sp}(vac) for this combination of propellants is ~260s and the recovery of specific impulse is around 85%. Improvements to specific impulse are being contemplated by increasing the percentage of AP upto 30% and addition of ultra fine powder of Aluminum and Boron with other catalysts.

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