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Design and Testing of Lab-scale Red Fuming Nitric Acid/Hydroxyl-terminated Polybutadiene Hybrid Rocket Motor for Studying Regression Rate

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ABSTRACT

This paper presents the design of a hybrid rocket motor and the experiments carried out for investigation of hybrid combustion and regression rates for a combination of liquid oxidiser red fuming nitric acid with solid fuel hydroxyl-terminated Polybutadiene. The regression rate is enhanced with the addition of small quantity of solid oxidiser ammonium perchlorate in the fuel. The characteristics of the combustion products were calculated using the NASA CEA Code and were used in a ballistic code developed for predicting the performance of the hybrid rocket motor. A lab-scale motor was designed and the oxidiser mass flow requirements of the hybrid motor for the above combination of fuel and oxidiser have been calculated using the developed ballistic code. A static rocket motor testing facility has been realised for conducting the hybrid experiments. A series of tests were conducted and proper ignition with stable combustion in the hybrid mode has been established. The regression rate correlations were obtained as a function of the oxidiser mass flux and chamber pressure from the experiments for the various combinations.

Keywords: Hybrid rocket motor, regression rate, oxidiser mass flux, chamber pressure, solid fuel, liquid oxidiser, RFNA, HTPB, red fuming nitric acid, hydroxyl-terminated polybutadiene

NOMENCLATURE

a	Constant in regression rate correlation
A_b	Regressing surface area
A_e	Nozzle exit area
A_p	Port area
A_t	Nozzle throat area
C^*	Characteristic velocity
C_F	Thrust coefficient
D_p	Instantaneous port diameter
G_o	Oxidiser mass flux
L	Length of grain
m_f	Mass flow rate of fuel
m_o	Mass flow rate of oxidiser
m_n	Mass flow rate through nozzle throat
M	Molecular weight of combustion products
n, m	Index in regression rate correlation
P_a	Ambient pressure
P_e	Nozzle exit pressure
P_c	Chamber pressure
$\dot{r}$	Regression rate
R_p	Instantaneous port radius
T_c	Adiabatic flame temperature
t_h	Burn time in hybrid mode
V_c	Velocity of combustion products
Δt	Time increment
φ	Oxidiser-fuel ratio
ρ_f	Density of fuel
γ	Ratio of specific heats of combustion products
ξ	Combustion efficiency

1. INTRODUCTION

A research programme has been initiated to study the combustion phenomenon in a hybrid rocket motor using liquid oxidisers namely red fuming nitric acid (RFNA) and nitrogen tetroxide (N_2O_4), and hydroxyl-terminated polybutadiene (HTPB) with addition of small quantity of ammonium perchlorate (AP) as fuel. HTPB is the state-of-the-art binder used in solid propellant rocket motors and is considered 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. Though the regression rate characteristics of HTPB with a few oxidisers (such as liquid/gaseous oxygen and hydrogen peroxide) are available in open literature, such data is not available for RFNA or N_2O_4. Experimental studies are focused on obtaining reliable ignition and combustion over a range of oxidiser flux and chamber pressures near the stoichiometric values. The primary aim of this study is to generate data on regression rate characteristics for these oxidisers and fuel combinations.

Several techniques to enhance the regression rate of a solid fuel in hybrid combustion have been examined[1]. One of the effective ways of increasing the regression rates in hybrids is the addition of low levels of solid oxidiser such as AP in the fuel. This type of configuration is called 'mixed hybrid' due to the mixing of solid oxidiser and catalyst in the solid fuel. However, it is reported that the configuration retains all the characteristics of the hybrid system with regression rate enhancement as high as 300 percent[2].

The paper details the design of a hybrid rocket motor

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(HRM) and the test facility for conducting a series of experiments with various oxidiser/fuel combinations. The results for a set of experiments using RFNA as liquid oxidiser with HTPB and low levels of AP addition as fuel is presented. Regression rate correlations for the hybrid combinations were obtained as a function of oxidiser mass flux and chamber pressure.

2. BALLISTICS CODE

The design of the HRM is based on a code realised for predicting the performance of the motor. The code uses a zero-dimensional model to average the parameters at each instant of time. The nozzle throat diameter and oxidiser mass flow rates were held constant. A single-port cylindrical grain as shown in Fig.1 was used for the analysis. The grain is allowed to burn only on the cylindrical surface. Mass flow rate of the oxidiser was assumed to be constant and could be specified. It was also assumed that the regression rate does not vary along the length of the port.

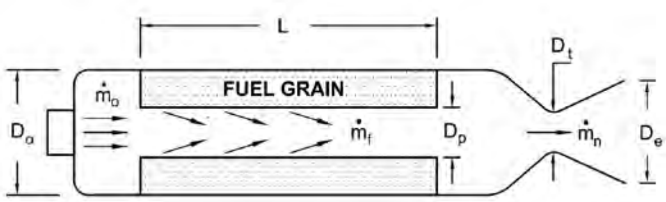

Figure 1. Motor geometry for ballistic model.

2.1 Theoretical Model

Conservation of mass at any instant of time neglecting the mass accumulation term is gives as

$$\dot{m}_o + \dot{m}_f = \dot{m}_n \quad (1)$$

where the fuel flow rate is

$$\dot{m}_f = \rho_f A_b \dot{r} \quad (2)$$

Regression rate of the hybrid fuel is generally a function of several variables such as oxidiser mass flux, port diameter, grain length, and pressure. The oxidiser mass flux through the port is the most predominant variable and addition of AP in small quantity makes it sensitive to the chamber pressure as in the case of a solid propellant. Therefore, the regression rate of fuel for these experiments can be expressed as a function of G_o and P_c

$$\dot{r} = aG_o^n P_c^m \quad (3)$$

where the coefficients *a, n,* and *m* can be obtained experimentally.

2.2 Thermochemical Computation

The adiabatic flame temperature, molecular weight, and the ratio of specific heats of the combustion products were obtained from thermochemical computation using the NASA CEA[3] Code for equilibrium flow at different mixture ratios. The molecular formula and enthalpy of formation of the reactants were obtained from ICT Database of Thermochemical Values[4]. Figures 2-4 show the variation of the parameters for the RFNA/HTPB/AP reactants at various oxidiser/fuel ratios computed using the CEA code. These parameters are used as curve-fits in the ballistic code and interpolated for the instantaneous O/F ratio which changes with time during hybrid combustion.

The adiabatic flame temperature is maximum at an O/F ratio of 4.4, below the stoichiometric value of 4.9, i.e. for a slightly fuel-rich mixture. The molecular weight of

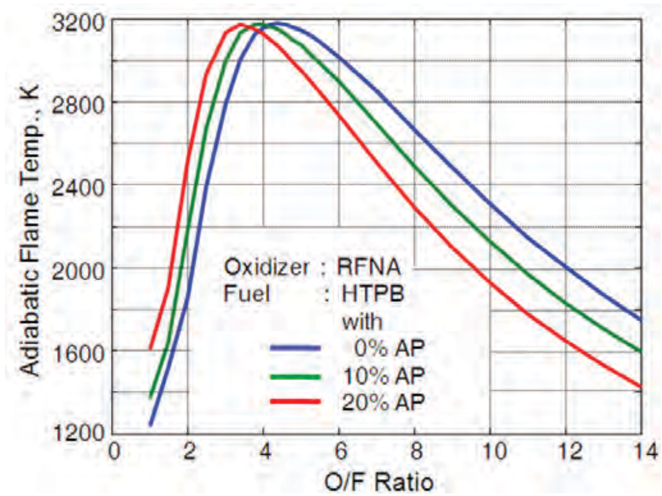

Figure 2. T_c *vs* φ for RFNA/HTPB combination.

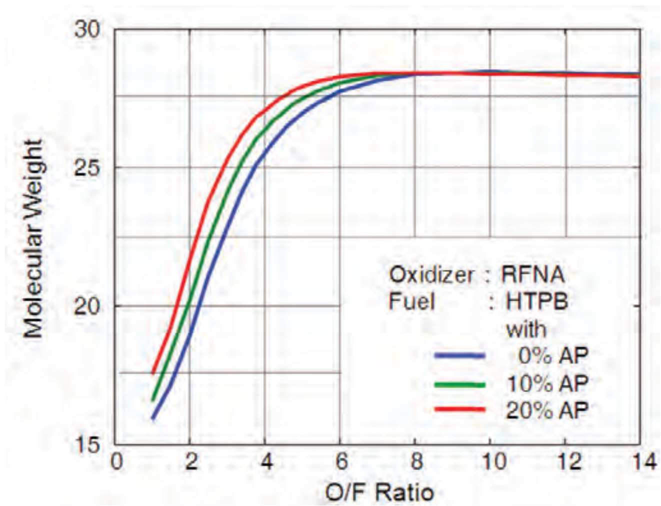

Figure 3. *M vs* φ for RFNA/HTPB combination.

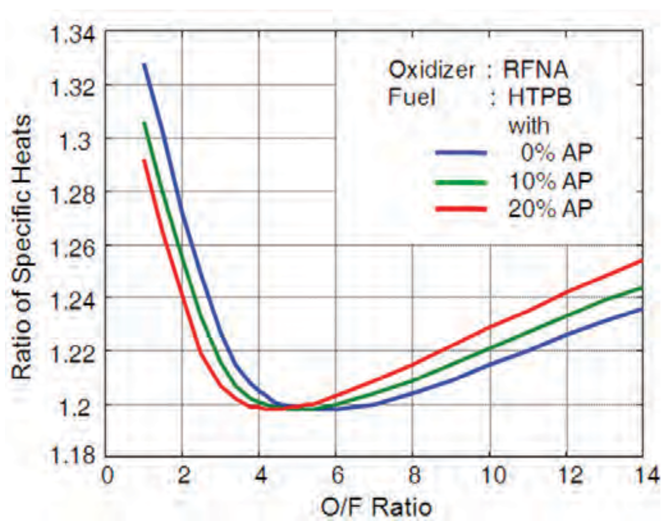

Figure 4. γ *vs* φ for RFNA/HTPB combination.

the combustion products increases steadily with O/F to a maximum value beyond the stoichiometric value. The ratio of specific heats is lowest and has minimum variation near the stoichiometric value.

2.3 Data Reduction from Experiments

The average O/F ratio during the operation of the hybrid motor was obtained from experiment (Eqn. 4) and the characteristics velocity C^*_{th} for this O/F ratio was computed using the CEA code.

$$O/F_{(avg)} = \frac{\int \dot{m}_o dt}{m_{f\,(total)}} \tag{4}$$

The characteristics velocity $C^*_{\exp}$ was obtained from the experiments (Eqn. 5), and the combustion efficiency factor, ξ was calculated and used in the ballistic code.

$$C^*_{\exp} = \frac{\int (P_c x A_t) dt}{\int \dot{m}_o dt + m_{f\,(total)}} \tag{5}$$

2.4 Computation of Rocket Parameters

The chamber pressure $P_{c(t)}$ for a time instant was obtained as

$$P_{c(t)} = \left[\dot{m}_o + \rho_f \ A_b \ a \ G_o^n P_{c(t-1)}^m\right] \frac{C^*_{\exp}}{A_t} \tag{6}$$

where $P_{c(t-1)}$ is the pressure at the previous instant.

Thrust and specific impulse at that instant were calculated using the standard equations

$$C_F = \sqrt{\frac{2\gamma^2}{(\gamma-1)}\left(\frac{2}{(\gamma+1)}\right)^{\frac{(\gamma+1)}{(\gamma-1)}}\left[1-\left(\frac{P_e}{P_c}\right)^{\frac{(\gamma-1)}{\gamma}}\right]} + \frac{(P_e - P_a)}{P_c}\frac{A_e}{A_t} \tag{7}$$

$$F = C_F P_c A_t \tag{8}$$

and $$I_{sp} = \frac{F}{\dot{m}_o + \dot{m}_f} \tag{9}$$

The instantaneous port radius was obtained as

$$R_{p,t+\Delta t} = R_{p,t} + \dot{r}\Delta t \tag{10}$$

The chamber pressure for the next time increment can be calculated from Eqn. (6) considering the increase in free volume due to the reduction in the web thickness of the fuel grain. The iterations will proceed till the instantaneous port radius becomes equal to the outer radius of the grain.

3. LAB-SCALE HYBRID ROCKET MOTOR

Using the ballistic code, performance predictions were obtained for a number of motor configurations. Computation was done with various grain geometries (outer diameter, port diameter, and length) and different oxidiser mass flow rates for arriving at the suitable design. Based on these results, geometry of the lab-scale hybrid rocket-motor has been derived for a range of oxidiser mass flow rates and pressures. The dimensions of the pre- and post- combustion chambers were kept fixed based on the considerations detailed in literature[5]. The schematic of the lab-scale hybrid rocket motor considered for the experiments is shown in Fig. 5.

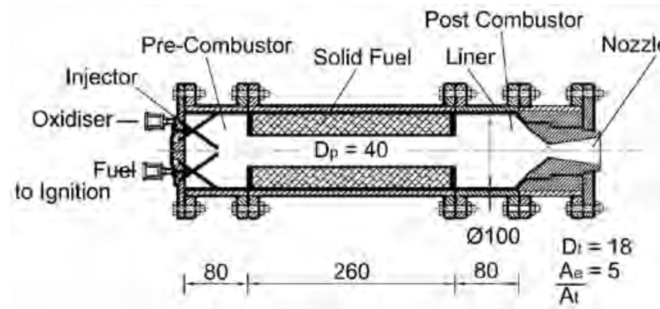

Figure 5. Geometry of lab-scale hybrid motor.

Since there are no experimental correlations available for regression rates for liquid oxidisers N_2O_4 and RFNA with HTPB, a correlation developed for gaseous oxygen/HTPB system by George[6], *et al.* was assumed initially for the motor design. This was updated later with experimental results obtained from static tests.

The estimated maximum mass flow rate of oxidiser requirement for the HTPB-RFNA combination is 0.06 kg/s in order to operate near the stoichiometric O/F ratio. Two types of injectors were designed for the above flow rate namely, doublet injector 4No. 90^o apart and pentode injector as shown in Figs. 6 and 7. The injector plates are provided with ports for the hypergolic fuel used with oxidiser for the ignition of HRM.

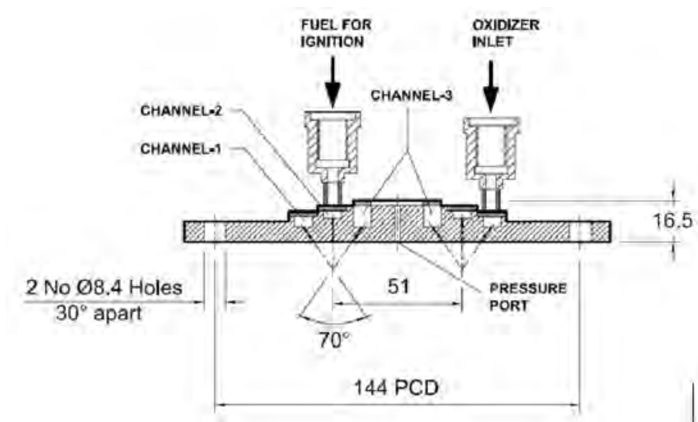

Figure 6. Doublet injector, 4 No. 90^o apart.

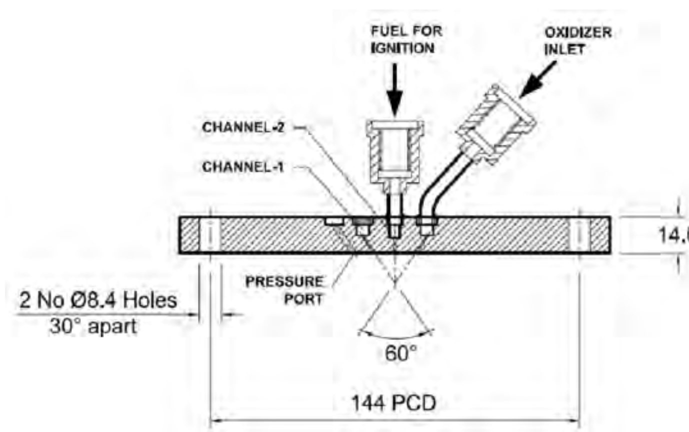

Figure 7. Pentode injector at the center.

4. EXPERIMENTAL SETUP

Figure 8 shows the scheme of oxidiser feed system for static tests of the lab-scale hybrid rocket motor. This 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 reinforced control room. The ignition of the system was provided by injecting hypergolic liquid fuel with oxidiser for a small duration. The chamber pressures were measured at the head end of the pre-combustor and at two locations in the post-combustor. Thrust was measured using a load cell. The HRM was purged with N_2 gas after the hot fire test.

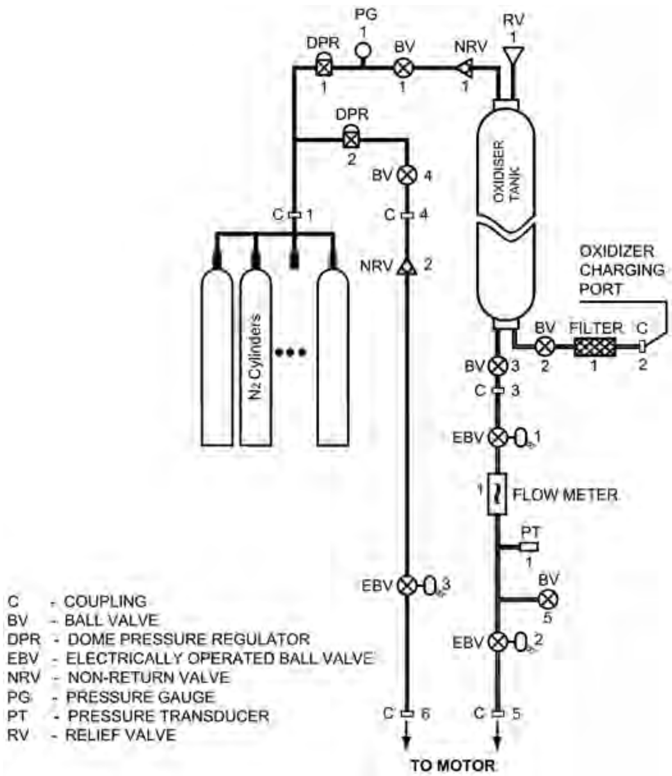

Figure 8. Oxidiser feed system.

5. HYDROXYL-TERMINATED POLYBUTADIENE GRAINS

The composition of the hydroxyl-terminated polybutadiene (HTPB) grains developed for the tests are given in Table 1. It is seen that for HTPB with addition of low percentages of 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 5 mm thick epoxy as shown in Fig. 9.

Table 1. Matrix of solid fuel 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

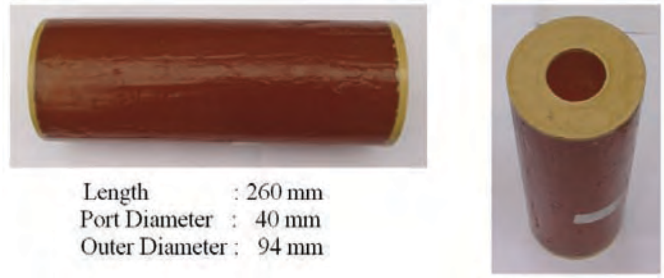

Figure 9. HTPB grain.

6. THE EXPERIMENTAL DETAILS

6.1 Initial Tests

The aim was to establish the ignition process followed by hybrid combustion and grain-02 was used for these tests. A flow rate of ~75 gm/s was considered for the first test and the predicted chamber pressure was ~10 bar. RFNA was injected for ~5 s through the fuel port before ignition using the hypergolic fuel. The hypergolic fuel was switched offand a weak and inconsistent exhaust flame was observed in the hybrid mode. The chamber pressure was ~2 bar and the average port diameter was 46 mm after the static firing in hybrid mode for 9 s. The following conclusions can be arrived from the test namely, (a) The initial flow of RFNA before ignition led to accumulation of oxidiser in the pre-combustor and the flooding of the motor, (b) after ignition this caused a highly oxidiser rich flow through the solid fuel port giving a very weak combustion, and (c) the weak combustion along with the wetting of the fuel port resulted in a poor regression rate of the solid fuel.

Based on the above observations, its was decided to start ignition simultaneously with the injection of the liquid oxidiser. Also, to prevent any oxidiser accumulation in the pre-combustor, the configuration of the pre-combustor was modified for direct injection of oxidiser into the fuel port by introducing an insert as shown in Fig.10.

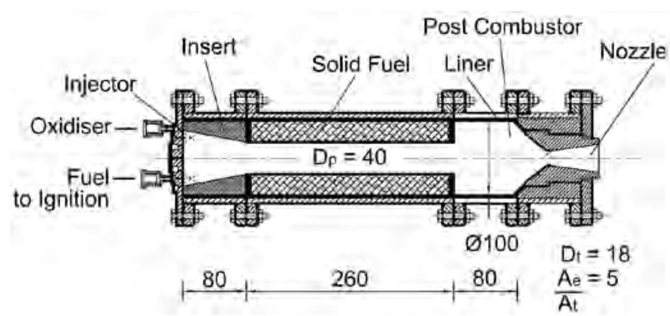

Figure 10. Motor configuration for ignition test 02.

However, start of hybrid combustion could not be established with the given modification. It was observed that the oxidiser flowed out of the nozzle as liquid. This test established the fact that a hot gas re-cirulation zone is essential ahead of the solid fuel for the liquid oxidiser spray.

6.2 Tests of HTPB with 20 Percent AP and RFNA

Based on the average regression rate of 0.3 mm/s obtained in test 01, the required oxidiser flow rate was reduced to ~35 gm/s. Accordingly, the nozzle was changed with throat diameter and area ratio of 8.0 mm and 6.25, respectively, to increase the chamber pressure. The insert considered in the pre-combustor chamber for the second test was removed. The grain-03 with 20 per cent AP content in the fuel was considered. The configuration of the motor used for the test is shown in Fig.11.

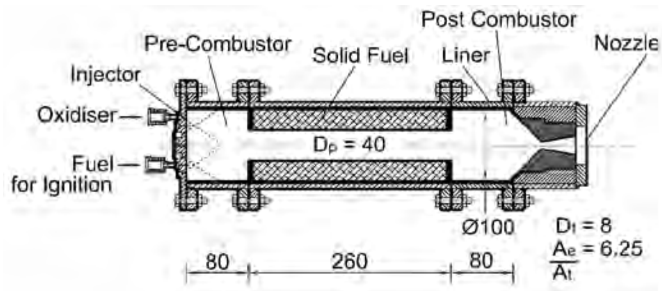

Figure 11. Motor configuration for static test-1A.

The statictest (1A) was initiated with the simultaneous injection of RFNA and ignition fuel for ~4 s. Ignition time was increased as the oxidiser flow rate was reduced. The motor functioned well in the hybrid mode for 18.3 s till the oxidiser was switched off. The exit flame was observed to be stable indicating efficient hybrid combustion. An average chamber pressure of 14.2 bar and thrust of ~8.5 kgf was measured. It was observed that the combustion was stable and the small pertrubations in pressure were well within limits of ±3 per cent.

The test was repeated (2A) for the same grain with a pentode injector at an average oxidiser flow rate of 83.5 gm/s. The chamber pressures and average port diameters before and after the two static tests using HTPB with 20 per cent AP and RFNA are given in Table 2.

Table 2. HTPB with 20 per cent AP (grain-03) and RFNA

Test No.	t_h (sec)	$\dot{m}_o$ (gm/s)	P_c avg (bar)	D_{pi} (mm)	D_{pf} (mm)
1A	18.3	38.0	14.2	40.0	64.0
2A	17.2	83.5	18.6	64.0	85.0

6.3 Tests of HTPB without AP and RFNA

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

For test 1B, the ignition time was kept almost the same as for that of test 1A. The motor functioned well in the hybrid mode for ~23.5 s till the oxidiser was switched off. The small pertrubations in pressure was well within the limits of ±3 per cent. The exit flame was stable indicating efficient hybrid combustion. Throat erosion started after ~17s and was seen from the constant drop in chamber pressure. The test (2B) was repeated for the same grain with a pentode injector for an average oxidiser flow rate of ~84 gm/s. The test conditions for the tests of pure HTPB fuel and RFNA are given in Table 3.

Table 3. HTPB without AP (grain-01) and RFNA

Test No.	t_h (s)	$\dot{m}_o$ (gm/s)	P_c avg (bar)	D_{pi} (mm)	D_{pf} (mm)
1B	23.5	58.0	18.8	40.0	57.6
2B	10.2	83.5	26.5	57.6	65.7

6.4 Tests of HTPB with 10 per cent AP and RFNA

A new grain-02 with 10 per cent AP content in the fuel was considered in the test (1C) with a flow rate of ~62gm/s. The nozzle throat was modified by introducing a tungsten-copper insert to avoid throat erosion. The ignition time was kept around 2 s. The motor functioned well in the hybrid mode for ~15.4 s till the oxidiser was switched off. The test (2C) was repeated for the same grain with a pentode injector for an average oxidiser flow rate of 76 gm/s. The test conditions for the two tests of HTPB with 10 per cent AP and RFNA are given in Table 4.

Table 4. HTPB with 10 per cent AP (grain-02) and RFNA

Test No.	t_h (s)	$\dot{m}_o$ (gm/s)	P_c avg (bar)	D_{pi} (mm)	D_{pf} (mm)
1C	15.4	62.0	40.0	57.0	24.0
2C	17.5	76.0	57.0	72.6	29.2

6.5 Test Measurements

The total mass of oxidiser used in hybrid mode was obtained by integrating the measured data. The total mass of fuel consumed was found by weight measurement after each test. The port diameter variation over the length of the grain was measured axially at four angular orientations (90^o apart) and was found to be within ± 3 mm, indicating negligible variation in regression rate in the axial direction. Typical measurement of port diameter for test (1A) is shown in Fig.12. The mass of fuel consumed through weight and volume measurements compares within 3 per cent accuracy.

The average O/F ratio during the operation of the hybrid motor was computed (Eqn 4) and the corresponding C^*_{exp}

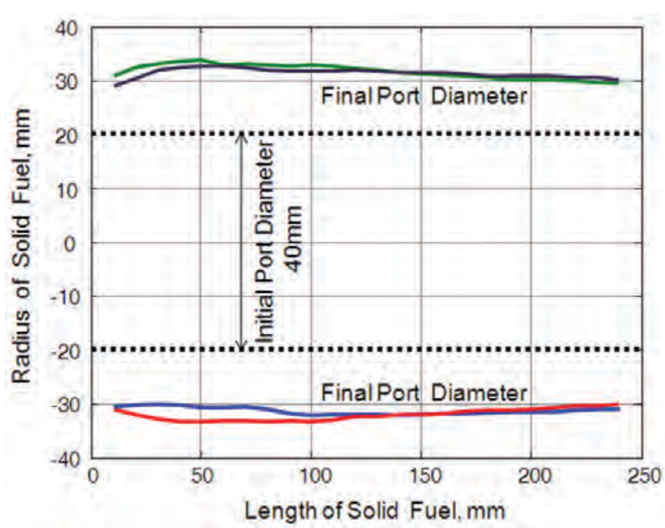

Figure 12. Port diameter variation for test-1A.

obtained from the chamber pressure data and oxidiser flow rate as given in Eqn (5). The combustion efficiency factor, ξ for each test was obtained experimentally and used in the ballistic code.

7. DATA ANALYSIS

The ballistic code is primarily used to obtain the accurate regression rate expression from the tests. In this method, it is important to note that the chamber pressure and the weight of fuel consumed for the test duration were matched for different test conditions.

7.1 Regression Rate Correlation

The regression rate is a strong function of the oxidiser mass flux and this relation[7] is used to arrive at a near value for the constant *n*

$$O/F = \frac{\dot{m}_o}{\dot{m}_f} \sim \frac{\dot{m}_o}{\dot{m}_o^n (A_b / A_p^n)} \qquad (11)$$

Thus,

$$\frac{O/F}{\dot{m}_o^{1-n}} \sim \frac{A_P^n}{A_b} \sim D^{2n-1} \qquad (12)$$

From this relation, it can be concluded that the value of (O/F)/ $\dot{m}_o^{1-n}$ must be a constant for a given combination of fuel and oxidiser at different oxidiser flow rates[7]. The oxidiser flow rate and average O/F derived from the experiments were used in Eqn (12). The value of *n* was chosen to converge the quantity (O/F)/ $\dot{m}_o^{1-n}$ corresponding to the tests with the same grain. The appoximate values of *n* thus obtained are 0.45, 0.5 and 0.65 corresponding to tests with pure HTPB, and HTPB with 10 and 20 per cent AP grains.

Since small percentages of AP were added in grains 02 and 03, it is hypothesised that these grains will have dependence on the chamber pressure as in the case of solid propellant. Regression rate studies of mixed hybrid with GOX and HTPB having up to 27.5-30.0 per cent AP have been conducted by Frederick, *et al.* and a pressure exponent of 0.21-0.23 was derived for these combinations[2]. This is about half the value (*m*~0.4) for a general HTPB/AP solid propellant case. The pressure exponent *m* for the present grains having 10 and 20 per cent AP in HTPB can be considered proportionately.

Starting with the initial values of *n* and *m* and applying in the ballistic code, the exact expression of the regression rates for the various fuel-oxidiser combinations have been derived by iteration, by matching the actual pressures and mass loss of solid fuel obtained from experiments, and are given in Table 5.

Table 5. Regression rate correlation with RFNA

Test	Fuel	Correlation
1A/ 2A	HTPB + 20%AP	$\dot{r} = 1.0\times10^{-5} G_o^{0.64} P_c^{0.15}$
1B/ 2B	HTPB + 0%AP	$\dot{r} = 6.0\times10^{-5} G_o^{0.44} P_c^{0.02}$
1C/ 2C	HTPB + 10%AP	$\dot{r} = 1.81\times10^{-5} G_o^{0.51} P_c^{0.10}$

7.2 Prediction and Comparison with Results

The ballistic code is used for the prediction of performance of the hybrid motor for HTPB with 20 per cent AP and RFNA, which is given in Table 6. The mixture ratio varies during the burn time and the combustion efficiency factor between 0.84-0.86 was obtained for the two tests. The test 1A was conducted for a low oxidiser mass flow rate with the O/F ratio between 1.6-1.8, and low specific impulse near 160 s is obtained. This has improved to ~190 s in the test 2A for higher O/F ratio. It may be noted that the higher burn rate of the solid fuel has contributed for the lower range of O/F ratio. The variation of oxidiser mass flux calculated from the tests 1A and 2A is between 31.0 to 14.0kg/m^{2}s.

Table 6. Performance prediction for HTPB with 20 per cent AP and RFNA

Test	O/F range	ξ	G_o (kg/m^{2}s) range	I_{sp} (s) range
1A	1.5 - 1.7	0.84	31 - 14	158 - 162
2A	2.5 - 2.7	0.86	30 - 17	183 - 190

The pressure time traces for the above tests are shown in Fig. 13. The higher pressure during ignition could be controlled and kept to a reasonable value. The effect of throat erosion is considered in the prediction and compares well with the experiments.

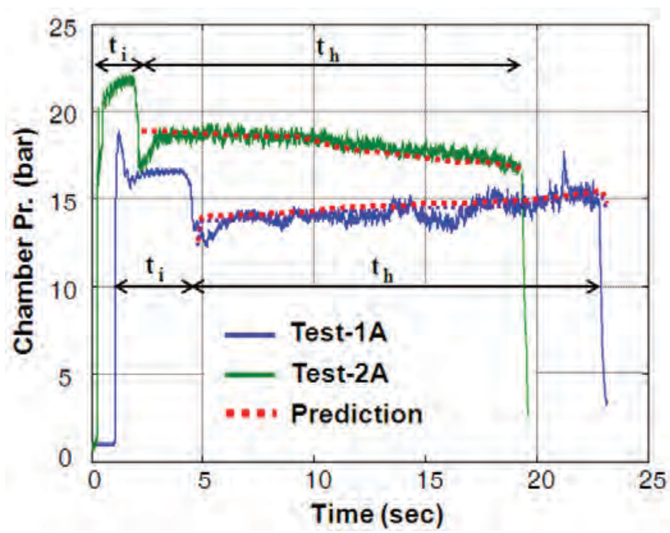

Figure 13. P_c vs Time for test 1A and 2A.

The performance prediction of the tests for the pure HTPB grain and HTPB with 10 per cent AP are given in Tables 7 and 8, respectively. The comparison of the prediction with the chamber pressures are given in Figs 14 and 15. A reasonably good prediction of chamber pressure is got for different grain configurations and oxidiser mass flow rates.

The I_{sp} estimated for the above experiments using the ballistic code was compared with the theoretical values for different mixture ratios in Fig. 16. Typical test of the hybrid motor is shown in Fig. 17.

8. CONCLUSIONS

Hybrid motor experiments were conceived for RFNA as liquid oxidiser and solid fuel namely HTPB with and without

Table 7. Performance prediction for HTPB and RFNA

Test	O/F range	ξ	G_o (kg/m^{2}s) range	I_{sp} (s) range
1B	4.5 - 4.7	0.92	47 - 26	195 - 198
2B	5.0 - 5.3	0.93	33 - 26	204 - 210

Table 8. Performance prediction for HTPB with 10 per cent AP and RFNA

Test	O/F range	ξ	G_o (kg/m^{2}s) range	I_{sp} (s) range
1C	3.5 - 3.7	0.93	57 - 25	210 - 213
2C	3.9 - 4.1	0.95	34 - 20	217 - 218

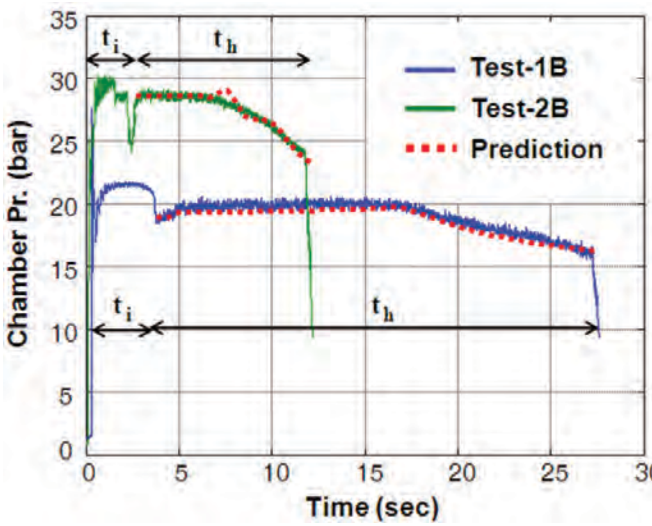

Figure 14. P_c ***vs*** **time for test 1B and 2B.**

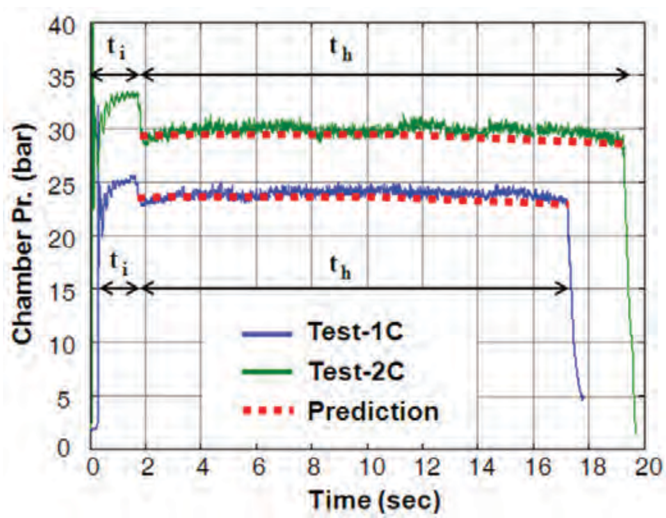

Figure 15. P_c ***vs*** **time for test 1C and 2C.**

the addition of AP. The design of a lab-scale HRM was based on a ballistic code developed with initial regression rate assumed from the literature. An experimental setup for conducting the static tests of the motor has been realized.

A set of hybrid experiments have been conducted with RFNA as oxidiser and solid fuel HTPB with addition of 0, 10

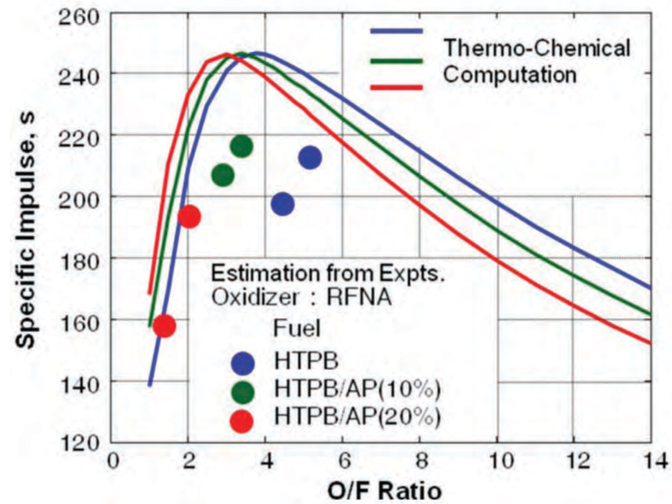

Figure 16. Estimation of I_{sp} **from experiments.**

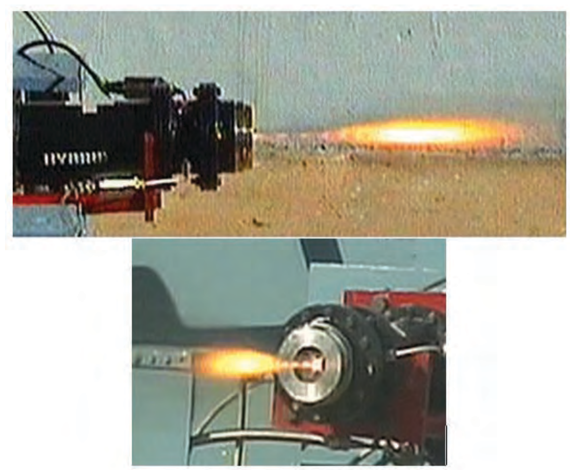

Figure 17. Static test of lab-scale hybrid motor.

and 20 per cent solid oxidiser AP. Initial tests were conducted to establish the ignition process and to evolve correct ignition parameters to obtain stable hybrid combustion. Stable combustion within a variation of chamber pressure ±3 per cent and combustion efficiency of up to 0.95 were achieved. The port diameter is nearly constant throughout the length of the fuel grain after the tests.

The regression rate correlations obtained from the present experiments revealed that the HTPB fuel with 20 per cent AP has higher regression rate, which in this case is nearly 100 per cent that of the pure HTPB fuel. Addition of solid oxidiser AP in small quantity in the fuel decreases the heat of degradation of the solid fuel, leading to propotionate increase in regression rate. New regression rate correlations for liquid oxidiser RFNA with solid HTPB fuel having 0, 10 per cent and 20 per cent AP were derived from the experiments as a function of oxidiser mass flux and chamber pressure. Performance predictions indicatethat the specific impulse is of the order of 210s. Improvements to specific impulse are being contemplated by increasing the percentage of AP up to 30 per cent and addition of ultra fine powder of aluminum and boron with other catalysts.

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REFERENCES

1. Venugopal, S.; Rajesh, K.K. & Ramanujachari, V. Hybrid rocket technology. *Def. Sci. J.,* 2011, **61**(3), 193-200.
2. Frederick Jr, R.A.; Whitehead, J.J.; Knox, L.R. & Moser, M.D. Regression rates study of mixed hybrid propellants. *J.Propul. Power*, 2007, **23**(1), 175-80.
3. Gordon, S. & McBride, B.J. Computer program for calculation of complex chemical equilibrium compositions and applications. *NASA Reference Publication 1311*, 1996.
4. Fraunhofer-Institut für Chemische Technologie. ICT database of thermochemical values. Computer Code Version-3, 2001.
5. Wernimont, E.J. & Heister, S.D. Combustion experiments in hydrogen peroxide/polyethylene hybrid rocket with catalytic ignition. *J. Propul. Power*, 2000, **16**(2), 318-25.
6. George, P. & Krishnan, S. Fuel regression rate in hydroxyl-terminated-polybutadiene/gaseous oxygen hybrid rocket motors. *J. Propul. Power*, 2001, **17**(1), 35-42.
7. Paul, P.J.; Mukunda, H.S.; Narahari, H.K.; Venkataraman, R. & Jain, V.K. Regression rate studies in hypergolic system. *Comb. Sci. Technol.*, 1981, **26**, 17-24.

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