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On Performance Evaluation of a New Liquid Propellant

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Abstract. A blend of 3-carene and cardanol in 70:30 weight proportion exhibits synergistic hypergolic ignition with red fuming nitric acid (RFNA) as oxidizer. Attempts have been made to evaluate this new propellant by theoretical calculation of performance parameters and verification of the results by static firing of a 10 kg thrust rocket motor around 20 atmosphers of chamber pressure. At an oxidizer-to-fuel weight ratio (*O/F*) of 3.34 (RFNA used had 21% N_2O_4 and 5% by weight of concentrated sulphuric acid as catalyst), the propellant produced a reasonably smooth pressure-time curve with an ignition delay of 35 milliseconds. The theoretical characteristic velocity value matched well with the experimental. No carbon residue was left in the rocket motor after firing. Specific impulse (theoretical) of the propellant has been found to be 223.8 seconds at chamber pressure, 20 atmos and exist pressure, 1 atmos.

1. Introduction

Hypergolic liquid propellants of specific interest in India are xylidine-triethylamine-red fuming nitric acid (RFNA), hydrazine-RFNA and unsymmetrical dimethylhydrazine (UDMH)-N_2O_4. Fuels like xylidine, triethylamine and UDMH, though indigenous and energetic are costly. In search of a low cost fuel, we found that 3-carene, a major constituent of Indian turpentine, when mixed with cardanol, a distillation product of cashew-nut-shell liquid, in 70 : 30 weight proportion exhibited synergistic hypergolic ignition with RFNA as oxidizer[1]. The ignition delay (ID) of the blend was measured in a modified **Pino's** ignition delay apparatus" at various oxidizer to fuel weight ratios (O/F). The minimum ID value of the fuel was found to be 48 milliseconds at ***O/F,*** 3.5 with RFNA (2 1% by weight of N_2O_4) mixed with 5% by weight of concentrated sulphuric acid. As theoretical performance of the propellant was evaluated by computer calculations, it became necessary to carry out the static firing trials to evaluate the propellant experimentally.

2. Experimental

2.1 Materials

3-Carene and cardanol (special grade) were obtained from **M/s** Camphor and Allied Products, Bombay and M/s Card-Chem. Ltd, Hyderabad respectively and used without further purification. A blend was made by mixing **3-carene** and cardanol in 70 : 30 weight proporation. The properties of **3-carene,** cardanol and their blend are listed in Table 1. The fuel blend is fairly safe to handle and has a good shelf life'. Its ID with RFNA did not change even after a year of preservation in the laboratory conditions.

Table 1. Properties of **3-carene,** cardanol and their blend (70 : 30 weight)

	3-Carene	Cardanol	**3-Carene-Cardanol** blend
Molecular formula	$C_{10}H_{16}$	$C_{21}H_{32}O$	$C_{7.347}H_{11.435}O_{0.1}$ (hypothetical)
Boiling point, °C	170-172	290-300	184185
Freezing point, °C	– *	-40	-40
Density, g/cc	0.8561	0.9523	0.869
Viscosity (at **30°C),** cps	1.23	52	2.393
Heat of combustion, **cal/g**	– 10,614	– 10,645	-10633.58

* Not determined but below-50°C

3-Carene was chosen instead of turpentine due to its lower ID with **RFNA** and higher resistance to the formation of resin during storage. RFNA was procured from the High Explosives Factory, Kirkee, Pune which contained HNO_3, 77%; N_2O_4, 21% and H_2O, 2% with specific gravity of 1.58 g/cc. Another variety of RFNA, supplied by the Launch Vehicle Control Systems Division of the Auxiliary Propulsion System Unit (APSU), ISRO, **Thumba,** containing HNO_3, 87.9%; N_2O_4, 10.3%; H_2O, 1.3% and HF, 0.5% was also used for static firing trials.

2.2 Methods

The ID measurements were carried out in a modified **Pino's** ignition delay apparatus reported by Kulkarni and **Panda**[2] earlier. Heat of combustion of fuels was measured by a Gallenkamp adiabatic bomb calorimeter in excess of oxygen atmosphere with benzoic acid as the standard. Performance parameters for different propellant systems were calculated by using a computer programme developed and run by the Explosives Research and Development Laboratory, Pune on a *Howtitt* **Pacard-98258** B desk computer.

The experimental determination of the performance parameters of different propellants were carried out by the static firing of a 10 kg-thrust rocket motor on the test bed at the Launch Vehicle Control Systems Division of APSU, ISRO, **Thumba.**

2.3 The Test Bed

Figure 1 gives the schematic of the test bed used in the static firing trials. Compressed nitrogen gas stored in a cylinder is employed for pressurizing the fuel and oxidizer tanks. The required pressure is obtained by using a pressure regulator. Upon opening of the solenoid valve (SV), the tanks are pressurized. The flow of fuel and oxidizer to the injector assembly is through their respective ball valves, filters, orifices and solenoid valves. The injector pressure and propellant tank pressure are measured by using a strain guage and associated bridge circuit. The rocket motor or thruster is vertically mounted on a bracket by means of a clamp.

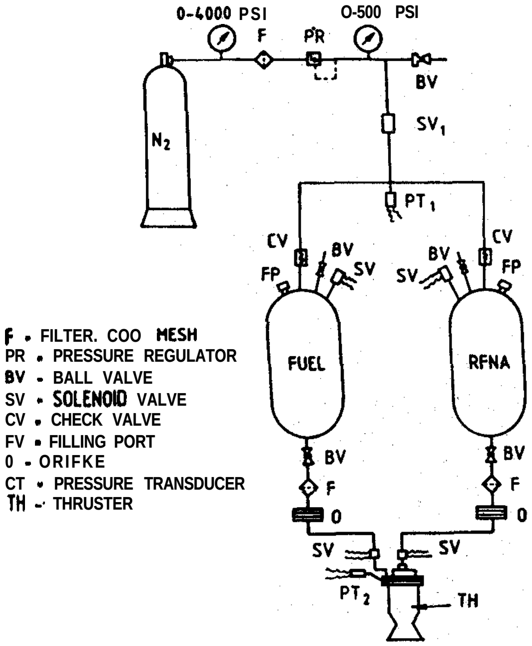

Figure 1. Flow schematic of thruster test set-up.

A 10 kg thruster, which was originally a component of India's SLV-3 and designed for hydra&e-inhibited RFNA (10% N_2O_4) was used for the reason of its ready availability at the place of firing. It consists of a stainless steel body to which is screwed a single element triplet impinging stream type of injector system where two streams of oxidizer impinge on a single stream of fuel. Impingement results in atomization of the liquid propellant into fine droplets with homogeneous distribution of fuel in oxidizer. The inner walls of the chamber and the nozzle are coated with an ablative liner consisting of Refrasil and Phenolic resin which can withstand continuous firing of 30 seconds. The throat insert is of tungston.

The control of firing and the recording of parameters (maximum 42 channels) was carried out in a control room. The parameters were recorded on UV recorders. Digital recording was also possible in many cases.

2.4 Flow Rate Calibration

In the present study, the flow rate calibration was carried out for five different *O/F* ratios and by using equivalent water flow rate values, suitable orifices were selected to get the desired *O/F* ratios. Table 2 gives the details of the calibration for 3-carene-cardanol-RFNA propellant. In actual practice only the approximate values of the flow rates given in Table 2 were realized. Thus a chamber pressure slightly lower than 20 atmos obtained during the calibration was considered satisfactory.

Table 2. Flow rate calibration for 3-carene-cardanol (70 : 30 by weight)

O/F ratios (by weight)	velocity C* (theoretical) m/sec	Total flow rate gm/sec	Flow rate					
			Fuel			Oxidizer		
			weight flow rate, g/sec	volume flow rate, cc/sec	equivalent water flow rate, cc/sec	weight flow rate, g/sec	volume flow rate, cc/sec	equivalent water flow cc/sec
5.12	1535.92	39.07	6.38	7.35	6.85	32.69	20.69	25.99
4.52	1563.23	38.39	6.96	8.01	7.46	31.43	19.89	25.01
3.94	1587.65	37.80	7.66	8.81	8.21	30.14	19.09	23.98
3.34	1599.47	37.52	9.95	11.45	10.67	27.57	17.45	21.93
3.00	1587.77	37.80	9.45	10.87	10.14	28.35	17.94	22.55

In order to find the minimum ID value, the static firing was carried out at all five *O/F* ratios for a short interval of time (300 milliseconds). The firing at each *O/F* was pulsed thrice (300 milliseconds of duration at each time with ten minute of interval). The ID (lapse of time between complete opening of the solenoid valves for oxidizer and fuel and rise in pressure in the combustion chamber to the 90% of its final value) was determined at each *O/F* ratio. It was observed that the ID values recorded for the second and the third pulses were smaller than the first. Thus, the ID values and the maximum pressure developed in the combustion chamber at each *O/F* were noted. From this, the experimental characteristic velocity (C^*) values were calculated using the formula,

$$C^* = \frac{P_c \times A_t \times g}{\dot{w}}$$

where

$A_t = 0.2970$ cms^2

and

$\dot{w}$ = total flow rate of oxidizer + total flow rate of fuel.

3. Results and Discussion

Table 3 and 4 give some of the important theoretical performance parameters of **3-carene-cardanol-RFNA** and UDMH-RFNA propellants respectively at chamber pressure (Pc), 20 atmos and exit pressure (Pe), 1 atmos. The RFNA composition was assumed to be HNO_3, 76%; N_2O_4, 21% and H_2O, 3%. For the **3-carene-cardanol** RFNA system, it can be seen from the Table 3, that the characteristic velocity (C*) and the specific impulse (I_{sp}) increase gradually from *O/F*, *5.12* (stoichiometric) to 3.34 to reach their maximum values after which both the parameters fall with decreasing

Table 3. Theoretical performance of **3-carene-cardanol** (70 ; 30 by weight) blend with RFNA as oxidizer

O/F (by weight)	Chamber temperature T_c (°K)	Exhaust temperature T_e (°K)	Characteristic velocity, C* m/sec	Specific impulse, I_{sp} sec
5.12 (Stoichiometric)	3137.53	1877.5	1535.92	216.075
4.82	3155.71	1885.46	1549.68	217.95
4.52	3167.92	1888.58	1563.23	219.76
3.94	3162.52	1871.68	1587.65	222.86
3.34	3070.73	1790.87	1499.47	223.84
3.00	2903-81	1662.04	1587.77	221.34

Table 4. Theoretical performance of UDMH-RFNA system

O/F (by weight)	Chamber temperature T_c (°K)	Exhaust temperature T_e (°K)	Characteristic velocity C^* m/sec	Specific impulse I_{sp} sec
3.39	3139.03	1876.74	1606.61	225.20
3.00	3160.07	1882.34	1636.84	229.25
2.50	3099.08	1823.27	**1665.05**	232.57
2.00	2845.91	1627.12	1659.17	230.49
1.50	2360.54	1279.61	1593.45	219.89

O/F ratio. Thus, the maximum theoretical I_{sp} obtainable for the propellant at P_c = 20 atmos is 223.8 seconds. At this O/F ratio the propellant has an average density of 1.32 g/cc which makes the density impulse 295.38 sec. g/cc.

For UDMH-RFNA, maximum C* and I_{sp} were observed at O/F, 2.5; the maximum theoretical I_{sp} at P_c = 20 atmos being 232.57 seconds. However, at this peak performance, the average density of the propellant is 1.216 g/cc and the density impulse, 282.71 sec g/cc. Thus for unit volume of the propellant, the 70 : 33 blend of 3-carene and cardanol stands ahead of UDMH in performance with RFNA as oxidizer. However, UDMH-RFNA is a well established propellant. Though 3-carene-cardanol is hypergolic with RFNA like UDMH, its ID is brought down below 50 milliseconds using 5% by weight of H_2SO_4 as a catalyst. Further the fuel blend being of hydrocarbon type where some unsaturation exists, it remained to be tested by static firing for its combustion efficiency and instability and the amount of carbonoceous residue left after firing. Thus the static firing trials were conducted for 3-carene-cardanol-RFNA system with two different compositions of RFNA at 20 atmos of chamber pressure in a 10 kg thrust rocket motor as described earlier. It was observed that when RFNA having a lower N_2O_4 content 10.3% was used with 2% by weight of H_2SO_4 added as ID catalyst, the pressure-time curve contained a number oscillations of varying frequencies (Fig 2). The ID value recorded was also high (50 milliseconds at O/F, 3.33). In order to overcome the problem, firings were conducted by using RFNA containing 21% of N_2O_4 with 5% by weight of H_2SO_4 added to it and the chamber pressure set at 19.291 kg/cm². The ignition delay measurements were carried out at different O/F by pulse firing. The minimum ID value was found to be 35 milliseconds at O/F, 3.34. A continuous firing for 10 seconds duration was conducted at this O/F to obtain a reasonably smooth and constant pressure-time curve (Fig 2). No carbon residue was left in the rocket motor after firing and flushing with nitrogen under pressure.

Table 5 lists the ID values (static firing) and calculated and experimental C* values at different O/F for 3-carene-cardanol-RFNA propellant. It can be seen from the

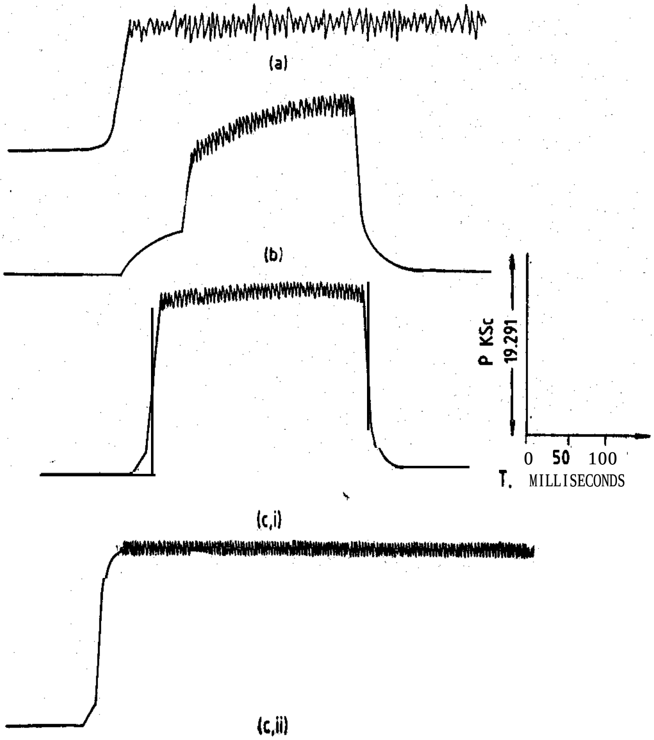

Figure 2. (a) Pressure-time curve for (a) **3-carene-cardanol-RFNA.** (10.3% N_2O_4) a O/F, 3.30 under continuous firing at 10 seconds. (b) **3-carene-cardanol-RFNA** (21% N_2O_4) a, O/F, 5.1213 (stoichiometrice) under pulsed firing for 300 milliseconds (c) **3-carenecardanol-RFNA** (21% N_2O_4) at O/F, 3.34 under (i) pulsed firing for 300milliseconds and under (ii) continuous firing for 10 seconds.

Table 5. I. D. and C* for 3-Carene cardanol blend and RFNA by static firing (P_e = 1 atmos)

O/F (by weight)	I.D millisec	C* calculated[a]	C* experimental[b]
5.12	245	1535.91	1305.05
4.52	125	1563.23	1366.32
3.94	55	1587.65	1483.93
3.34	35	1599.47	1583.98
3.00	45	1587.77	1561.11

a-RFNA composition : HNO_3, 76%; N_2O_4, 21% and H_2O 3%;
b-FNA composition : HNO_3, 77%; N_2O_4, 21%; H_2O, 2%; mixed with concentrated H_2SO_4 5%; P_c, 19.291 Kg/cm^2 (ksc) obtained during calibration.

Table that ID decreases with decreasing O/F making the propellant fuel rich. Thus the minimum ID, 35 milliseconds was recorded at O/F, 3.34. At the same O/F, the calculated and experimental C* values reached their maxima and closely agreed with each other indicating the limit of combustion efficiency obtainable for the propellant under the firing conditions. The pressure time curve recorded was smooth and constant unlike those obtained earlier (Fig 2). Thus, the results were highly encouraging. In addition, the cost of the fuel blend is around Rs. 7.00 per kg making it highly attractive for large rocket motors. This in turn, necessitates the optimization of the performance of the propellant through the proper hardware design.

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