REGRESSION RATE STUDIES OF A PARAFFIN-BASED HYBRID ROCKET

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Abstract. *Hybrid motors have regain attention for future applications in aerospace science. Because standard hybrid fuels have limited combustion velocities, such engines are not use commercially for space application. The use of hybrids rockets, though, may increase operational safety, decrease on site emissions was well as reduce costs over current solid fuels. The propulsion team from the Energy and Environment Laboratory – University of Brasília, has been investigating a promising solid fuel for hybrid rockets, based on paraffin. A large number of tests indicated reliable ignition and stable combustion over a large operational envelop. This paper show the measured solid fuel regression rates obtained for paraffin-based solid fuel and nitrous oxide. In a 500 N motor with 75 mm inside diameter, we were able to get regression rates as high as 4.5 mm/. An effort to present a mathematical correlation for the combustion velocity as a function of oxidizer mass flux and pressure fail due to lack of confidence in measuring the rate of oxidizer injection. Our tests, though, confirmed that paraffin-based solid fuel may burn up to three times faster than conventional hybrid fuels, such as HTPB. Since ignition and stable combustion were observed in the majority of the tests, these propellants might open important opportunities for hybrid rockets in space applications.*
Keywords*: hybrid rocket, paraffin, nitrous oxide, regression rate.*

1. Introduction

The propulsion team from the Mechanical Engineering Department – University of Brasília (LEA-UnB) is conduction research in hybrid rockets for a couple of years. More recently, the propulsion group has been investigating a new type of solid fuel, paraffin, whose regression rate is three to four times faster than conventional hybrid fuels, such as HTPB (Aerospace America, 2002). A model rocket based entirely on this technology was successfully conceived, built and launched, in December 2004, by our propulsion team. The rocket used paraffin as the solid fuel and nitrous oxide as the oxidant. Next step, as a demonstrative project, our group will test a sounding rocket, capable of reaching 20000 meters, sponsored by AEB (Brazilian Space Agency) on the scope of the Uniespaço program. Conceptually, this rocket should delivery about 4500 N for 25 seconds. Two other groups are working on this project, one from *Instituto Tecnológico de Aeronáutica* and the other from the Mechanical Engineering Department - *PUC-Rio*. In order to qualify the 4500 N engine, two less powerful motors, 700 and 1500 N, are under investigation. Qualification of the three engines is a key factor for success mission.

An important parameter for engine performance is the solid fuel regression rate. Data are available, so far, for paraffin and GOX (gaseous oxygen) for a broad range of oxidizer flow rate (Karabeyoglu et al. 2004). This paper is then concerned on fuel regression rate of paraffin and nitrous oxidize. Controlled experiments were conducted aiming to find a useful correlation relating solid fuel regression and nitrous oxide mass flux.

Karabeyoglu *et al*. (2002) analyzed the regression rate of hybrid rockets compared to other matured technologies. They claimed that despite their safety and cost advantages over solid and liquid systems, conventional hybrid rocket possess one very significant shortcoming: very low fuel regression rates. As a consequence, poor fuel loading and low thrust densities are observed. Correcting this by designing complex grain with multiple fuel ports results in larger residuals and compromised grain integrity. The limit on the regression rate for the conventional hybrid combustion configuration is set by the physical phenomena of heat and mass transfer from the relatively remote flame zone to the fuel surface. As a consequence, the regression rates of modern hybrid that utilize polymers as the fuel are much lower than conventional solid-rocket burning rate.

Timnat *et al.* (1986), performed experiments in hybrid motors showing that the factors which affect the regression rate of the solid fuel are the mass flux, the geometry, the pressure level and the presence of oscillations, the composition of the oxidizer and the burning time. They used polymethylmethacrylate (PMMA) and polyethylene (PE) as the solid fuel, in the pressure range 0.3 to 2,0 MPa. The regression rate calculated was in the range of 0.2 to 1.0 mm/s (mean value), with higher initial peaks. Pressure effects on the regression rate appeared to be stronger at low pressures. For PE the pressure effect were no longer observed near 1.0 MPa, while for PMMA the same trends took place at about 2.0 MPa. The characteristic velocity depends not only on the mixture ratio but also on the residence times of the combustions gases. They noted that pressure oscillations also enhance the regression rate. Initially regression rates in hybrid rocket motors tend to be markedly higher than later, during burning.

Chiaverini *et al.* (2000) conducted experimental investigation of the regression rate characteristics of hydroxyl-terminated polybutadiene (HTPB) solid fuel. In the research they burnt HTPB with oxygen. The hybrid motor was of a slab-geometry, windowed, allowing a real-time x-ray radiography system to obtain instantaneous solid-fuel regression rate data at many axial locations. Regression rates displayed a strong dependence on axial location near the motor head-end. In their studies it was finding a significant influence of the thermal radiation at lower mass flux levels and regression rates were also affected by the addition of activated aluminum powder. According to the authors a 20% by weight addition of activated aluminum to HTPB increased the fuel mass flux by 70% over that of pure HTPB. A correlation to relate the regression rate to operating conditions and port geometry was produced for both pure HTPB and HTPB loaded with certain fractions of activated aluminum.

Zakirov and Sweeting (2001) tested the space applications of nitrous oxide (N_2O) as a propellant system by comparing it to conventional systems. The research found many reasons to affirm that nitrous oxide is a promising propellant for future low cost, small satellite missions. The experience obtained shows that:

- it can be stored in orbit and decomposed on a catalyst, decomposition generates heat and thrust - generated hot exhaust gases can ignite fuel upon contact.
- nitrous oxide cold-gas, monopropellant, resistojet, and bipropellant thrusters are feasible. The results of performance comparison of these systems show that application of nitrous oxide, being dense and liquefied is beneficial on volume-constrained small satellites.
- resistojet or monopropellant is beneficial on power-constrained small satellites.

Monopropellant and bipropellant will reduce major “safety overheads”. Multi-mode systems will be more effective over conventional single-mode alternatives. The following advantages of nitrous oxide multi-mode propulsion offer:

- higher total spacecraft velocity change performance over conventional single-mode alternatives;
- propulsion power budget reduction, design simplicity, ease of packaging and integration on spacecraft, firing strategy flexibility;
- increased number of mission scenarios and launch opportunities;
- reduction in propulsion system cost;
- in addition, power and oxygen-rich atmosphere can be generated on board the spacecraft by nitrous oxide decomposition.

Karabeyoglu *et al.* (2004) has led to the identification of a class of paraffin-based fuels that burn at surface regression rates are three to four times that of conventional hybrid fuels. The approach involves the use of materials that form a thin, hidrodynamically unstable liquid layer on the melting surface of the fuel. A series of scale-up test with gaseous oxygen had been carried out using a new Hybrid Combustion Facility (HCF) at NASA Ames Research Center. They show that data from these tests are in agreement with the small-scale, low pressure, and low mass flux laboratory tests at Stanford University and confirm the high regression rate behavior of the fuels at chamber pressures and mass fluxes representative of commercial applications. Altogether, they performed more than 300 firings of paraffin hybrid motors ranging in scale form 50,0 - 190 mm (diameter) producing 230 - 15600 N thrust, using both nitrous oxide and oxygen as oxidizers. Fuel grains up to 1140 mm long were tested.

Regression rate is the most important characteristic of a hybrid rocket fuel, and a better characterization of that quantity as a function of some other relevant operational variables is critical for a satisfactory design.

By combining the relative advantages of paraffin-based solid fuel and nitrous oxide we believe that the practical application of hybrid propulsion is far extendable. The main objective of this study is then to estimate the coefficients a and n that characterize fuel regression rate, by the correlation $r = aG^n$. Tests were conducted with solid paraffin and liquid nitrous oxide as the rocket propellants.

2. Experimental Setup and Methodology

Previous tests were conducted in a horizontal stand. Some firings are planed to take place in a "test as you fly" manner. As a consequence, a new vertical test stand was designed and built. The experimental apparatus had all the necessary instrumentation for proper data acquisition. A pneumatic valve remotely controls the oxidizer injection system. Figure 1 illustrates the test stand and main components. A nitrous oxide tank is turned upside down in order to fill the injection system with liquid oxidizer. Figure 2 illustrates the data acquisition system. The system is comprised of multi function data acquisition system, model NI AT-MIO-16E-2 with a sample rate of 500 kS/s (national Instruments). The primary elements were a load cell type MATC – 1,5t (*Micro-Análise*), an ECO-1, 60 bar, pressure transducer (Wika) and a B&K pressure transducer, 200 bar. All the data is processed under LabView platform and post-processed in a work sheet chart.

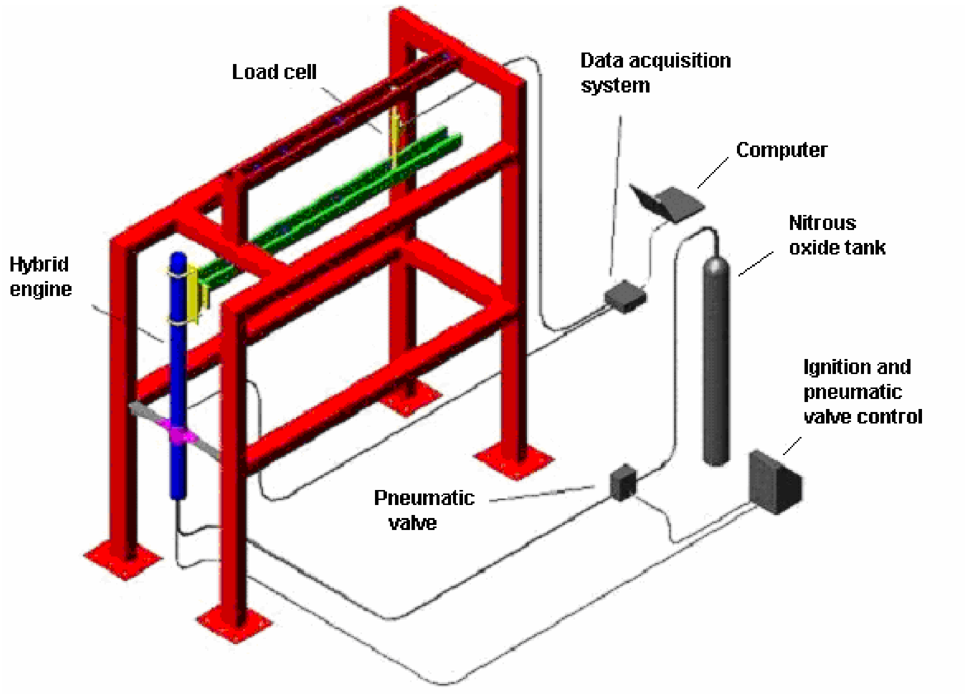

Figure 1. Drawing of the vertical test stand.

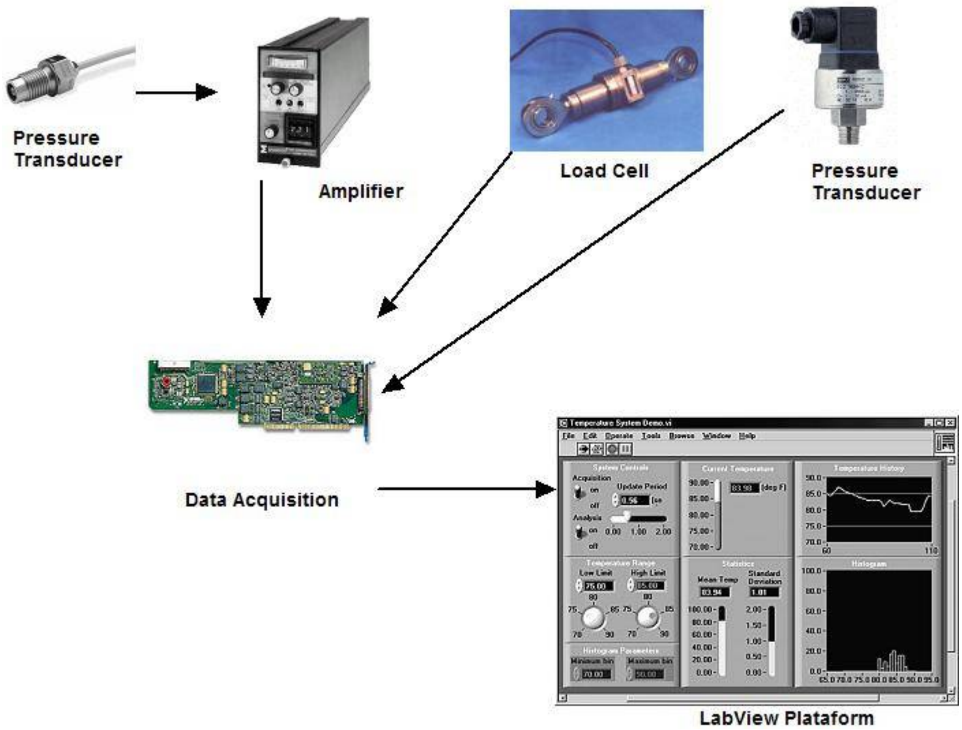

Figure 2. Data acquisition system.

A perforated plate was used as the injection head. The amount of oxidizer was previously estimated by the equation

$$\dot{m} = C_d A \sqrt{2 \rho \Delta P} \tag{1}$$

In Eq. (1), C_d is the discharge coefficient, A is the cross sectional area, ρ is the oxidizer density and ΔP the pressure drop through the injector. Three injectors were fabricated with 10 holes of 0.5, 0.78 and 1.4 mm diameter, with calculated flow rates of 60, 150 and 460 g/s, respectively. Figure 3 shows the injector plate along with the estimated mass flow rate. The mass flow rate was verified experimentally with a pressurized water tank for three different levels of pressure drop, 10, 15 and 20 bar. The measured C_d was calculated as 0.551.

Figure 3. Injector plate.

Figure 4 shows a photograph of the injection head where it can be seen the perforated plate, the pneumatic valve and the pressure transducer.

Figure 4. Rocket and main subsystems prior to firing in the vertical stand.

To estimate the regression rate, the following procedure was adopted:

- casting the fuel grain with three levels of port diameter;
- measuring port diameter at three different locations (endings and middle);
- weighting the grain before the firing;
- burning the fuel to completion;
- mathematical estimation of fuel regression rate.

By keeping the mass flow rate constant, mass flux was varied by altering grain initial port. The idea of burning the fuel to completion relies on the relatively low melting temperature of the paraffin. It is very difficult to freeze the processes of phase changing and combustion after interrupting the flow of nitrous oxide. Inevitably a considerable amount of fuel may be lost in the extinction phase. A PVC tube, for grain casing, was used in all firings. We then, advanced the firing time as to consume the casing after the paraffin was burnt to completion. The time for burning the PVC was previously estimated and the combustion phase of the paraffin was corrected by diminishing the PVC burning time. Thrust signal and video images were also employed to verify the transition from paraffin burning to PVC.

3. Results and Discussion

Several paraffin grains were fabricated. Details of fuel processing can be seen in Santos and Oliveira (2004). Basically, liquid paraffin with a blackening agent is poured in a PVC tube (fuel casing), 220 mm length and 71 mm internal diameter. The casing rotates for a one and half-hour at 1500 rpm. The casing is maintained when firing because it protects the paraffin against cracking and for thermal protection of the rocket walls.

A typical thrust measurement can be seen in Fig. 5 and 6.

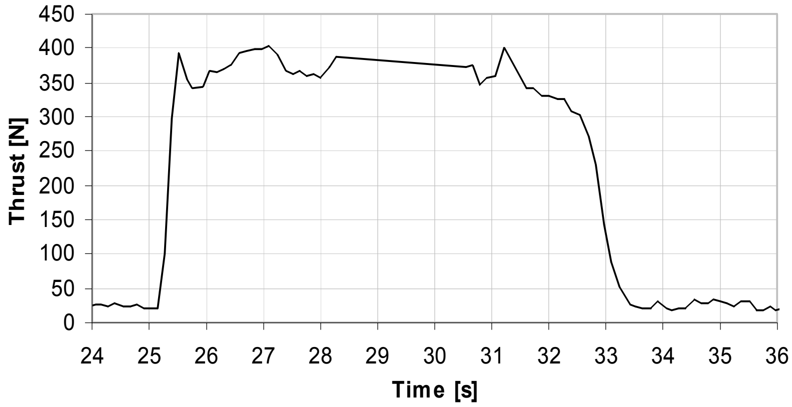

Figure 5. Thrust curve versus time for test number 9.

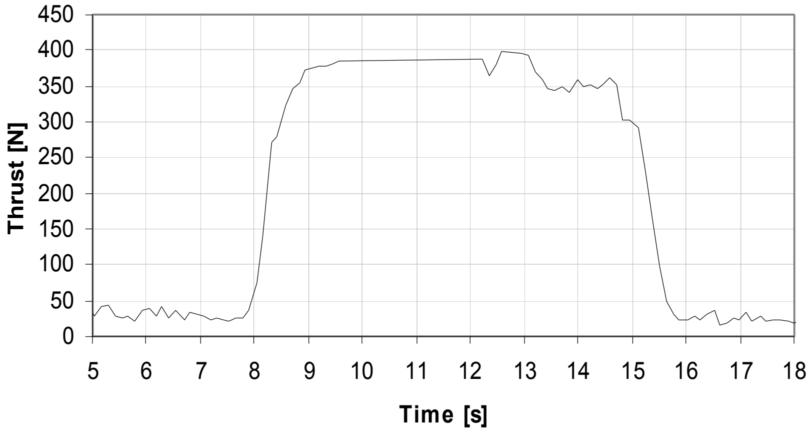

Figure 6. Thrust curve versus time for test number 10.

Thrust ranged from 350 to 400 N. In Fig. 5, the transition to a lower level thrust occurred at about 31 seconds, when the paraffin vanished and PVC (grain casing) initiated burning. The same trends are also observed in Fig. 6. The transition is even clearer. The layer of paraffin burnt in test number 9 (Fig. 5) was 17.1 mm for which 5.68 seconds were necessary for complete combustion. Video records confirmed such observations. The regression rate can be estimated as 2.8 mm/s. In the case of test 10, the layer was 19.05 mm and the elapsed time was 5.9 s, which gives a regression rate of 3.7 mm/s. The regression rate of PVC is much lower than that of paraffin. The thickness of the PVC casing is about 5.0 mm for which the regression rates were estimated as 0.83 and 0.74 mm/s for tests 9 and 10, respectively.

In this research phase we performed fifteen firings. The first three were not considered due to very low thrust and chamber pressure. The injector plate with 0.5 mm holes did not match the available rocket nozzles. We, therefore, changed for the 0.78 mm holes injector's plate. With this new injector seven firings were done. The last two tests were discharged due to low level of oxidizer. Table 1 shows the results for the 0.78 mm injector's plate. With this set of data it was not possible to infer a correlation for the paraffin regression rate. We believe that the mass flux was not properly estimated. The oxidizer tank pressure is very sensitive to temperature. The temperature of the tank is greatly affected by nitrous oxide evaporation. We usually conducted three firings in sequence, with a time interval of about 15 minutes. All the firings were done at late night, when the average temperature is less than 20 °C, thus bringing tank pressure 10 bar less than at daytime. The pressure acquisition system seemed working no well as thrust measurements.

Three more tests were conducted with the 1.4 mm holes and the results are shown in Table 2.

Table 1. Experimental results for the 0.78 injector's plate (150 g/s).

Test number	*G* [g/cm^{2}s]	Regression rate [mm/s]	observation
1	18.6	2.0	Tank 1
2	20.2	2.1	Tank 1
3	9.6	1.6	Tank 1
4	12.0	1.5	Tank 1
5	20.2	1.4	Tank 1
6	Nv	Nv	Tank 1 empty
7	nv	nv	Tank 1 empty
8	13.5	2.7	Tank 2
9	15.0	2.8	Tank 2
10	17.0	3.7	Tank 2

Table 2. Experimental results for the 1.40 injector's plate (460 g/s) .

Test number	*G* [g/cm^{2}s]	Regression rate [mm/s]	observation
11	50.5	4.4	Tank 2
12	50.2	4.3	Tank 2
13	58.5	4.6	Tank 2

The last three firings, with very high oxidizer mass flux produced a relatively high regression rate. The average regression rate for the PVC casing was 0.78 mm/s. The average thrust obtained for these firings were in the range of 650 to 800 N.

Once more, the attempt to get a good correlation for the fuel regression rate failed. Since the paraffin layer and the combustion time are less prone for errors, we believe that our mass flux estimation was poor. We will improve the data acquisition system in order to measure the oxidizer mass flow. In any case, it is clear the high regression rate of the paraffin compared to other standard hybrid fuels.

Table 3: Regression rate and burning conditions of lab-scale hybrid motor (Chiaverini et al. 2001, adapted).

Test	Fuel	G_o (g/cm^{2}s)	P_c (atm)	*D* (cm)	O/F	r (mm/s)	Comments
5	HTPB	15.1	40.2	2.64	1.29	1.36	Large *P* oscillation
6	HTPB	11.4	25.9	3.20	1.88	0.87	Ultrasound
8	HTPB	8.2	25.5	3.21	1.67	0.72	X-ray, ultrasound
11	HTPB[1]	11.8	30.4	3.39	2.04	0.92	X-ray, ultrasound
20	HTPB	27.4	18.7	2.73	2.05	1.54	X-ray, ultrasound
21	HTPB[2]	17.4	27.3	3.24	1.96	1.25	X-ray. ultrasound

[1] HTPB + 0.25% carbon black powder, 75 nm, [2] HTPB + 20% Al.

Table 3 shows regression rates for HTPB and gaseous oxygen for a broad range of oxygen mass flux. As it is shown, the regression rate is a weak function of combustion chamber pressure a more dependent on oxidizer flow rate.

Also, efforts to increase regressions rates by adding carbon black powder and aluminum were, to some degree, disappointing. Comparing Test 5 and 21 the O/F ratio and pressure had stronger effects on burning velocities than the use of additive (Al). The O/F ratio, in Table 3, for oxygen and HTPB, lies between 1.29 and 2.05. In the case where nitrous oxide is the oxidizer, having paraffin as the solid fuel, the stoichiometric O/F ratio is around 9.5. Therefore, a hybrid rocket with these propellants operates with a very high mass flux, because of the combined effects of O/F ratio and the high regression rate of paraffin. The highest regression rate reported for HTPB, in Table 3, is 1.54 mm/s. This value was about the minimum we have got for paraffin and nitrous oxide, as shown in Table 1. Table 3 shows, for the burning velocity, a maximum around 4.5 mm/s in our experimental conditions.

4. Conclusions

In this work regression rates studies were conducted in order to verify the performance of paraffin and N_2O as propellants in hybrid rockets. Also, we tried to find a good correlation for the burning velocity against oxidizer mass flux. Our tests showed that paraffin burns stable with easy ignition even with nitrous oxide. The average regression rate for paraffin is much higher than those reported for HTPB standard fuels. The effort to get a correlation for regression rate was frustrating. The impossibility of finding the proposed correlation stem on the fact that oxidizer mass flux was difficult to estimate with good confidence. We planned to improve our data acquisition system as to correct this shortcoming. We could, however, confirm the high regression rate of paraffin-based solid fuel compared to other standard fuels used in hybrid propulsion. This would allow a single port for the majority of the applications in commercial field.

Currently, we are building a 1500 N hybrid rocket to be tested in the near future. After qualification of this motor the team will design and test a 4500 N hybrid rocket. Results regarding the operation of these hybrid motors will be published soon.

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