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TEST BENCH FOR MEASURING THE REGRESSION RATE OF SOLID PROPELLANTS

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Abstract.
This work presents a test bench design for linear burning tests of solid propellants. The Strand Burner Test is a technique to experimentally evaluate the linear burning rate of solid propellants samples. The propellant composition could be used in base-bleed gas generators and rocket motors. Despite the simplicity of the measuring bench built, it achieved good accuracy and provided a quick test procedure, allowing to improve the process of improving the propellant formulation with ease. The test bench can be used in propellant research and quality control during propellant production. In this work, the test bench was used to evaluate and improve the grain formulation of base-bleed gas generators, used to inject hot gases to decrease the base drag and increase the range of the projectiles. Base-Bleed gas generators operate at a low chamber pressure, close to the projectile's base pressure. Thus, the burning tests were performed under atmospheric pressure conditions. But the burn rate can be measured at lower or higher chamber pressures, found respectively in Base-Bleed operating at high flight altitudes and in rocket combustion chambers, with the aid of a small pressure vessel. Requiring only two or three electrical wires for its operation, the pressure vessel design is simpler and more compact. The test bench was made entirely of stainless steel. The propellant grain is fixed on a special support and, as the propellant sample linearly deflagrates, a set of fine wire filaments open in sequence, changing the voltage of the measurement circuit, through a resistive divider, which generates a voltage signal that can be used to detect the flame position along the propellant test sample. An electronic module, using an Arduino microcontroller commands the grain ignition and measures the voltage signal. A computer is connected to the module, and a special script in MatLab, process the data, calculates the linear burning rate, and plot the Voltage x Time graph. It will be presented that the linear burn rate measured during the tests was compatible with the literature related to similar propellant formulations.

Keywords: *base-bleed, strand burner, burning rate, solid propellant, composite propellant*

1. INTRODUCTION

Linear burning rate test of solid propellant ("Strand Burner Test") is a measurement technique to experimentally evaluate the regression rate, or burning rate, of solid propellant samples. Allowing to estimate and evaluate the operating conditions propelants of rocket engines, and to help in the subsequent simulations, involving the operational conditions of rocket motors. Allowing to calculate the combustion chamber pressure, thrust, adiabatic flame temperature, among others. The linear burning test is a relatively simple evaluation, however, due to the precision offered by the measurements and the direct way in which the results are obtained, the test is an excellent method both for research and for the control of the production of propellant grains, since it is possible to compare and evaluate propellant formulations Crawford *et al.* (1947). It is possible to compare and evaluate the performance of propellant samples very quickly, with safety and at low costs.

In (G Gupta, 2015) are presented many methods and techniques, to measure the burning rate of propellants. The tests can be performed primarily under constant pressure or constant volume conditions. In the first case, a large tank volume is needed (Miller and Holmes, 1988), to dampen the pressure variations resulting from the generation and expansion of gases generated during the combustion of the propellant sample under test, and, to keep the pressure approximately steady, a surge tank is necessary to stabilize the pressure. In constant volume tests (G Gupta, 2015), the burning test is performed inside a small pressure vessel of fixed volume, to contain the combustion of the grain and the generated gases. During a constant volume test, the pressure increases with the sample combustion process. During the tests the vessel volume is filled with a non-reactive gas to the combustion, or limiting the inlet of gases that can affect the combustion process. The gas pressure also influences the burnig rate of solid propellants (Atwood *et al.*, 2013), so it must be measured or controlled in some way.

It is noteworthy that the background of this work is the improvement of propellant formulations, applied to a Base-Bleed system for long-range munitions, where the internal combustion chamber pressure is slightly above the external pressure close to the projectile base. During the tests presented in this work, it was sought to restrict the tests to the expected operating conditions of the propellant grain, which occur at atmospheric or sub-atmospheric pressure, as show in (Miller and Holmes, 1988), (Mukhtar and Nasir, 2018) and (Zhang *et al.*, 2017). The Base-Bleed description of the present application can fe found at (Lemos *et al.*, 2017).

The construction and validation of a burning rate test system will be presented in this work, as well as the tests of some propellant grain formulations under atmospheric pressure conditions.

The research related to the present work aims to analyze the influence of the composition and the granulometry of the oxidant Ammonium Perchlorate on the linear burning rate of composite propellants. The results obtained in the tests have been successfully used in simulations (Pinheiro *et al.*, 2020), (Lucena *et al.*, 2020), analysis and improvement of propellant formulations. As well as simulations and estimates, in order to determine the regression rates of the propellant grain inside the combustion chamber, at the expected operational pressures and when subjected to high spin rate, in which the tested propellants will operate effectively as show in (Lemos *et al.*, 2022), along the trajectory of a ballistic device, for military use by the Brazilian Navy, under development at the Instituto de Pesquisas da Marinha (IPqM) and at the Fábrica Almirante Jurandyr da Costa Müller de Campos (FAJCMC).

2. METHODOLOGY

2.1 The Linear Burning Test Bench

The linear burning test was introduced by Crawford *et al.* (1947), where the author also describes the burning test setup. Another example of burning test bench construction is at (A Aziz and Ali, 2013). To perform the linear burning test of propellant grain samples, it is necessary to use a test bench, as described by the standard (MIL-STD-286C, 2010). The present test bench is composed by the grain propellant suport, the electronics module and the processing software.

2.1.1 Grain Propellant Support

A support for fixing the propellant grain sample, which would also make it possible to ignite the sample and measure its burning rate, was designed and built. The design and mechanical construction of the support, as well as all the electronics and software were carried out in laboratories GESAR and LARISA, of the Rio de Janeiro State University (UERJ).

The physical structure of the test bench is made of stainless steel, to better resist the very high temperatures achieved during combustion of the propellant samples and to resist the thermal oxidation, when subjected to combustion products, with high levels of hydrochloric acid. The base show in Fig. 1 has a support for the propellant sample and a support plate to protect the electrical circuit against heat, in addition to fixing the screws and respective ceramic electrical insulators. All wiring uses special conductors and high temperature insulation.

2.1.2 Electrical and Electronics of the Test Bench

In addition to the mechanical structure of the test bench, the electrical and electronics systems were also developed to enable the safe ignition of the grain sample and the detection of the flame front of the sample during its combustion.

The electrical part of the test bench is composed by a set of fine metallic wires connected to a resistive voltage divider circuit. The connections to the thin metallic filaments are made through stainless steel bolts and nuts.

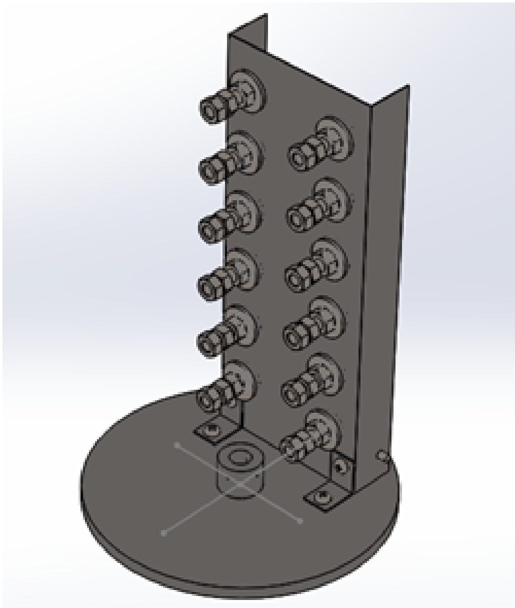

Figure 1. The base and support of the test bench.

The Fig. 2 shows the metallic filament opening detection circuit, where five heat-resistant wire resistors are used.

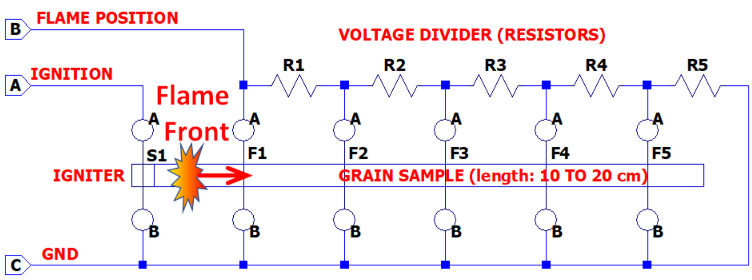

Figure 2. The electrical circuit of the test bench. Showing the igniter, the metallic filaments F1 to F5 and the propagation of the flame front. It requires only 3 wires to connect to the ignition and measurement electronics.

The resistors and the wire filanents are interconnected as an electrical voltage divider circuit, whose output voltage increases as the fine cooper filaments are fused by the flame front, from top to bottom in the grain sample, fixed to the support in vertical orientation. The ignition begins with the electrical activation of the ignitor S1, at the top of the grain, and the flame front propagates down the grain sample, and sequentially fuses the filaments F1 to F5. As filaments F1 to F5 fuse, the voltage between terminals B and C gradually increases, as shown in The Fig. 3. Points 1, 2 and 3 on the graph show the instants at which filaments F1, F2 and F3 are respectively fused by the flame front.

The electronics is responsible for measuring the opening time of each metallic filament, inserted in the grain sample and sending this information to the data capture and processing software. To allow the squib to be ignited and to measure the voltage between the B-C terminals of the circuit shown in Fig. 2, the circuit shown in Fig. 4 was developed and built.

In the circuit, a constant current source (U1) injects a current of a few milliamps between points B-C of Fig. 2, the voltage is measured by an Arduino, which also records the instants of time when each filament fuses. The voltage versus time data are sent to a computer, through an USB communication interface, in real time at the end of a burning test. The circuit also commands the ignition of the propellant sample, through the push button S1. To increase safety, the switch S2 is to enable/disable the ignition. By monitoring the igniter voltage, before and during ignition, electronics can determine a bad electrical connection, igniter failure and the moment when ignition occurs.

The voltage, measured between points B-C, versus time, is shown in Fig. 3, and is processed by a Matlab® script, to calculate the average value, to achieve a good measurement accuracy of the linear burning rate of the propellant sample. It should be noted that, the linear burning rate is determined in two or more sections of a sample, depending on the sample length, the filaments quantity and the distance between adjacent filaments. As the pressure is steady during the combustion of the sample, the burning rate is practically the same in the adjacent sections of the sample.

The Fig. 5 is another view of the electronics, the module panel, connected to the suport base, power supply and USB

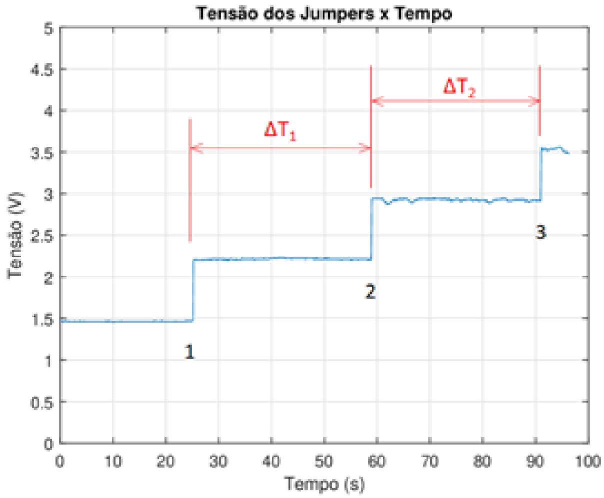

Figure 3. Voltage versus time graph. Voltage between the B-C terminals of the measurement circuit, during a linear burning test.

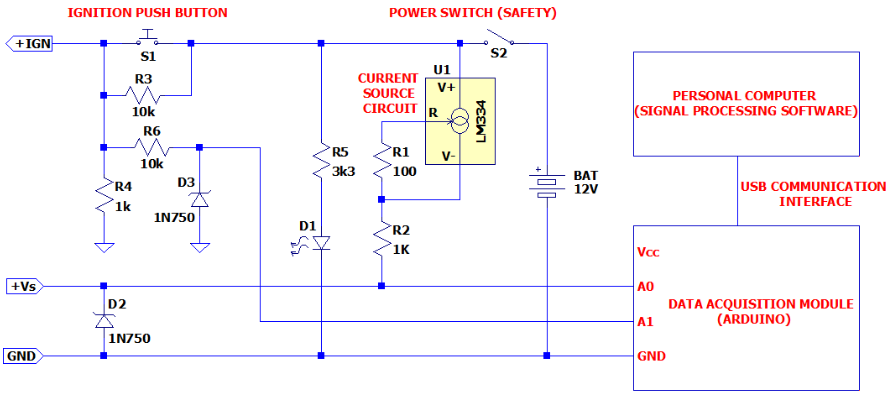

Figure 4. Ignition and measuring electronic circuit diagram.

interface.

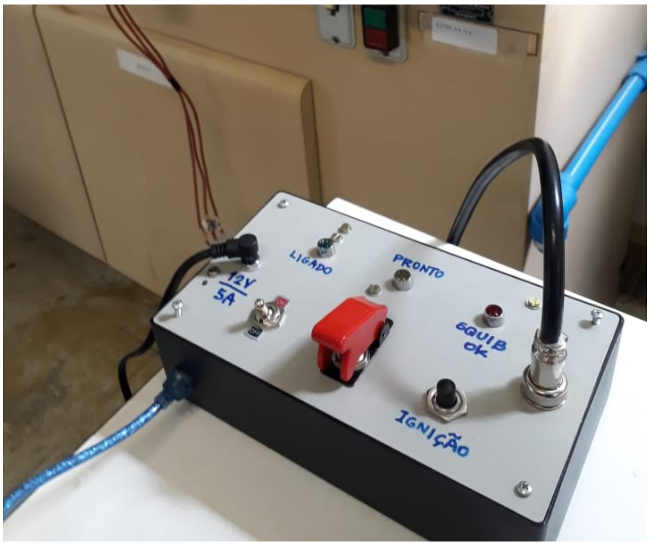

Figure 5. Electronic module panel.

2.2 Preparation of The Sample for The Burning Test

As shown in Fig. 6, before the test, the propellant grain sample is coated on the outside with a special plastic paint on the sides of the sample, to inhibit surface burning of the grain and limiting only to a cigarrete-like linear burning of the propellant sample. After the coating drying, tiny 30mm equidistant holes are made, crossing the grain sample, with the aid of a sewing needle and a drilling template. Then, the copper filaments are inserted, which will be fixed on the connection screws, to compose the electrical circuit for measuring the flame front. Due to the rubbery consistency of the composite propellant, the small holes are easily made, without any damage or cracks on the propellant sample. The minimum diameter of the sample of composite propellant must be oberved, as show in (Miller and Holmes, 1988), of 8 mm diameter. In this research the sample has a square section of 10 x 10 mm.

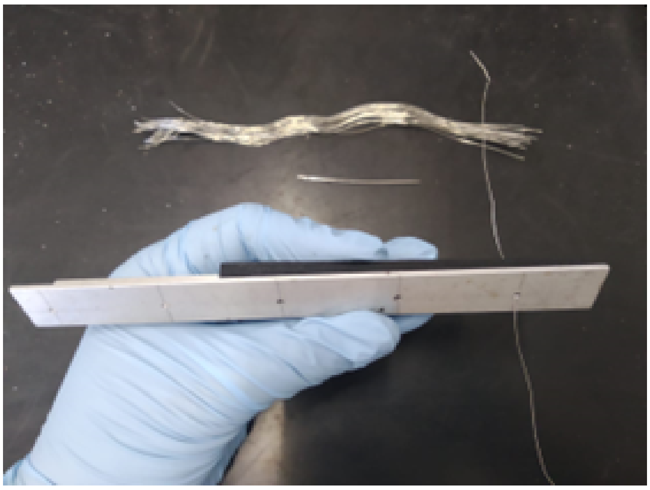

Figure 6. Filaments of nickel plated copper being inserted into a propellant sample.

In Fig. 7 the grain is fixed to the base and ready to start a linear burn test. Then the test base wiring is connected to the measurement electronics. It is possible to notice soot deposits on the support plate and some ceramic insulators, which gradually settle with the tests.

Figure 7. The base with a propellant sample, igniter and filaments, ready to start a new burning test.

3. RESULTS AND DISCUSSION

As already mentioned, all tests were performed at atmospheric pressure and room temperature. The tests were carried out with the test base inserted in a protective tube open at the top, to prevent the inlet and flow of air next to the sample under test. Thus, the atmosphere inside the tube (tube base) was basically from the gases and combustion products generated during each burning test. The Fig. 8 shows the bench just after performing a burning test of a propellant sample.

Figure 8. Test bench after combustion of the propellant sample. Note the propellant coating remained intact.

It was found that the base, made of 304 stainless steel, resisted heat very well. However, it is necessary to carry out periodic cleaning of the base, to avoid excessive deposits on the ceramic insulators. In the Fig. 8, it can also be seen that the propellant coating remained intact, even after combustion, indicating the suitability of the coating used. Not interfering with the burning and fulfilling its function, of restricting the burning to be predominantly in the vertical direction, from top to bottom in the sample.

As the graph shown in Fig. 3, a typical graph of voltage versus time during the burn tests, it is possible to perceive the moments when the filaments F1, F2 and F3 fuses, and with a sudden increase of voltage. Knowing the time interval between sucessive filament fusing, indicated in the graph as ΔT_1 and ΔT_2 and the distance d between adjacent filaments, of 30 mm, it is possible to calculate the linear burning rates $r = d/\Delta T$.

Tests were carried out with four grain compositions A, B, C and D. Containing a certain amount of the oxidant Ammonium Perchlorate (AP), aluminum powder (Al), ferric chloride (Fe_3O_4) and the plastic matrix, basically composed by HTPB (Hydroxyl-terminated polybutadiene). The Tab.1 presents a summary of the results of linear burning rate measurement, obtained with each composition, formulations A, B, C and D.

According to the table, comparing compositions A and B with composition C, when increasing the mean diameter of the oxidant grains (AP), the mean linear burning speed decreases. These results, burning rate around 1 mm/s, are compatible with tests with propellants of similar composition, obtained in (Miller and Holmes, 1988). As for composition D, which has a smaller grain size of oxidant (AP), a higher percentage of oxidant and an additive to increase the burning rate (magnetite - Fe_3O_4), a higher rate was measured.

4. CONCLUSION

The present work presented the development, construction and tests of a test bench for linear burning rate test of solid propellants under constant pressure.

The test base built resisted the heat very well, despite the need for cleaning after some tests.

The propellant coating used did not interfere with the burning and restricted the burning to a one direction only, along the length of propellant samples.

The electronic circuit and the software, written for Matlab®, were able to detect the fusing of the wire filaments,

Table 1. Relationship between different propellant formulations, Ammonium Perchlorate (AP) granulometry, the average linear burning rate and respective Standard Deviation.

Propellant Formulation	Mean AP grain diamenter (μm)	% AP	% Al	% Fe_3O_4	% Plastic Matrix	Linear Burning Rate (mm/s)	Standard Deviation
A	290	76	2	-	22	0.965	0.042
B	290	76	2	-	22	0.93	0.051
C	145	76	2	-	22	1.055	0.004
D	120	80.48	-	0.5	19.02	1.354	0.016

through a simple and effective design. Being able to determine the linear burning rate of propellant samples quickly, simply and reliably.

The results obtained, of linear burning rate, were compatible with the literature, of propellants with similar composition to the one evaluated. Where the increase in the percentage of oxidant (AP) and the reduction in the granulometry of the oxidant caused an increase in the rate of grain regression. The inclusion of the burning rate additive (Magnetite) also generated an increase in the burning rate of the samples, as expected.

5. ACKNOWLEDGEMENTS

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7. RESPONSIBILITY NOTICE

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