

DEVELOPMENT AND DESIGN OF A WORKBENCH FOR ROCKET MOTOR TESTING

Igor Seiiti Kinoshita Ishioka, igorseiiti@zenitaerospace.com

Ramon Carim Bevilaqua, ramonbevilaqua@gmail.com

Faculdade UnB - Gama, St. Leste Projecção A, Gama, 72444-240, Brazil

Erlan Rodrigo de Souza Cassiano, erlan.neo@gmail.com

Faculdade de Tecnologia UnB, Asa Norte, Brasília, 70910-900, Brazil

Pedro Luiz Kaled da Cás, pedrokdc@gmail.com

Faculdade de Tecnologia UnB, Asa Norte, Brasília, 70910-900, Brazil

Artur Elias de Morais Bertoldi, artur.bertoldi@aerospace.unb.br

Faculdade de Tecnologia UnB, Asa Norte, Brasília, 70910-900, Brazil

Manuel Nascimento Dias Barcelos Júnior, manuelbarcelos@aerospace.unb.br

Faculdade de Tecnologia UnB, Asa Norte, Brasília, 70910-900, Brazil

***Abstract.** This work describes the development and design of a new workbench for propulsion testing of hybrid rocket motors. Therefore, the main goal is to overcome design limitations of traditional workbench projects. In order to facilitate the thrust measurement, non-conventional design concepts are employed, such as the use of a system of rails and rollers to lower friction. This solution is preferred over the common used cantilever systems because it makes the mounting of the rocket motor simpler, once the movement of the set is restricted to one direction. Other than increasing the thrust measurement accuracy, the new support leads to an easier handling of the system and enables the use of different rocket motors, in a range from hundreds of Newtons up to 3,500 Newtons of thrust.*

***Keywords:** hybrid motor, test bench, hybrid rocket, chemical propulsion, experimental research*

1. INTRODUCTION

Chemical systems of aerospace propulsion are classified into three different categories: solid, liquid and hybrid engines (Sutton, 2010). Liquid engines generate propulsion by the reaction of two propellants in liquid phase, while solid motors generate thrust by combustion of a propellant grain auto-oxidant. The standard hybrid propulsion motors produce thrust by the reaction of an oxidant fluid with the fuel vaporized in the interior of a solid propellant grain, the reverse configuration with liquid fuel and an oxidant grain has also been tested (Sutton, 2010).

Historically, hybrid engines have suffered from several difficulties, the most important: low solid fuel regression rates compared to solid motors; small combustion efficiency (~ 90%) and low combustion efficiencies generating moderate specific impulses. These features and the industry's virtual satisfaction with the current status have discouraged research into hybrid rocket propulsion. Recently, it was noticed a renewed interest in the hybrid rocket engine propellant, primarily due to the lower cost of development, the relative safety and higher specific impulse when compared with solid engines.

Several technologies originally developed for hybrid engines may be adapted to be applied in solid and liquid engine designs, among them we mention: cryogenic oxidants (Sutton, 2010), the oxidant injection and pressurization system (Bertoldi, 2007), regenerative nozzle (Veras, 2011), new pair of oxidant and fuel additives (Karabeyoglu, 2012). Although for the validation of each of these technologies are required extensive experimental campaigns.

The test bench built at University of Brasília (UnB) shown in Fig. 1 was operated by the Hybrid Propulsion Team, propelled by nitrous oxide (NOX) and paraffin or gaseous oxygen (GOX) and paraffin, both oxidizers in gaseous phase. The design of the test bench aimed versatility and withstand a motor of 500 N (Veras et al., 2010). The motor easily adapts to changes, such as the doping of the fuel grain, the nozzle cooling and regeneration, among others. Based on the experience acquired during more than three years of operation of this system, a set of design guidelines have been accumulated to assist in the development of new test benches (Barcelos et al., 2012), these guidelines were the basis for the project of the new family of experimental benches at UnB.

The creation of the Aerospace Engineering course at UnB Campus Gama (FGA) together with the plan to install a Chemical Propulsion Laboratory (LPQ) motivated the development of a new test bench to be operated in such facility. The main guidelines behind the project of the new test bench were: the use of hybrid engines of different sizes and configurations; ergonomics; capability of performing a sequence of tests in a short time; data acquisition with reliability and safe systems.

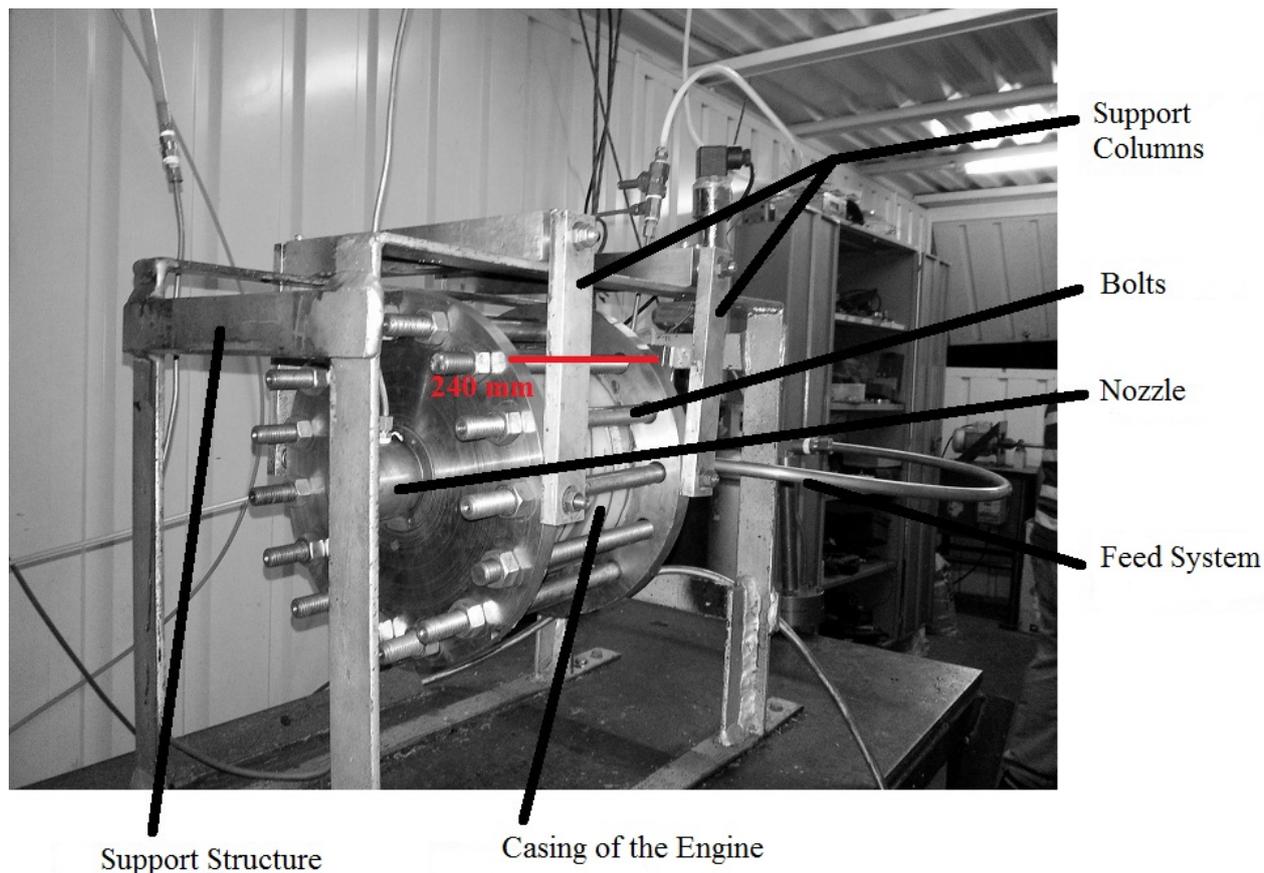


Figure 1. Propulsion bench of Campus Darcy Ribeiro.

2. HYBRID ENGINE PROJECT

The new experimental test bench was developed in order to evaluate the performance of several rockets under design by the UnB Hybrid Propulsion Team. However, for this work the sounding rocket denominated LILE-2 will be employed to qualify the test bench. Based on the performance requirements of LILE-2, the motor (Fig. 2) must generate an average thrust of 300 N for a 7 s powered flight.

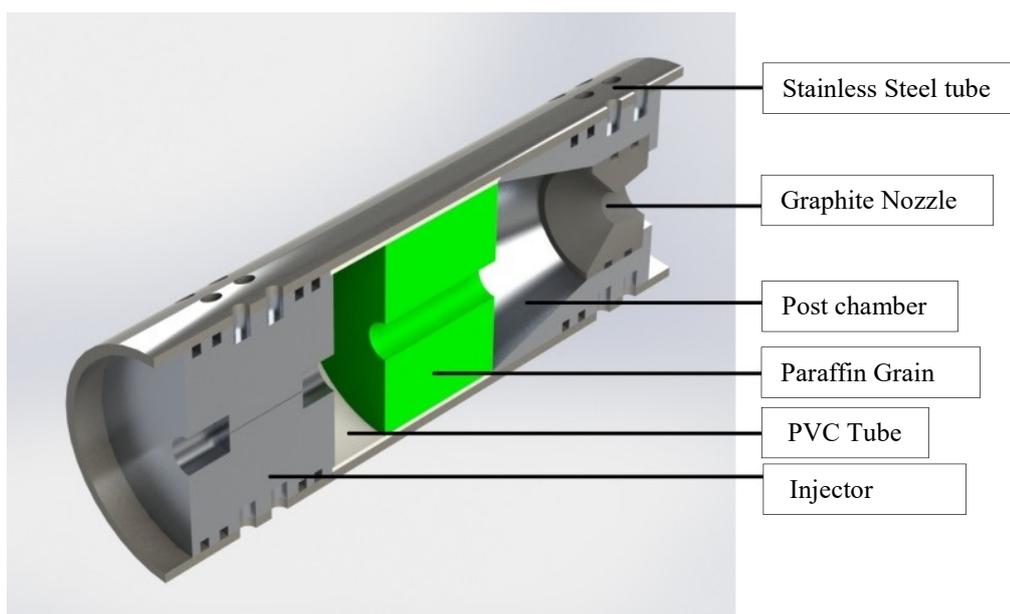


Figure 2. 3D diagram of the LILE-2 hybrid motor.

2.1 Internal ballistics

The motor of the sounding rocket LILE-2 has paraffin and nitrous oxide as propellant, this because the reasonable specific impulse and great familiarity of the UnB team with such pair. Complementarily, the re-pressurization property of the nitrous oxide proved to be an extremely useful feature for the propulsive system of a flight model (FM), where simplicity is essential. Nitrous oxide has medical usages and is available in the Brazilian market without restrictions, while the wax used (PARAFINA 140 / 145°F) is manufactured by the Brazilian company Petrobras. For the design of the bench and the motor, it was employed an optimization methodology that has already been applied to multidisciplinary hybrid rockets developed at UnB (Kaled da Cás, PL, 2012) by the Hybrid Propulsion Team. Such methodology is based on the prediction of the engine operation by using five variables which are subsequently optimized with the use of genetic and gradient algorithms. The variables are:

- Outlet diameter of the propellant grain “ D_g ”.
- Propellant grain inner diameter “ D_{in} ”.
- Propellant grain length “ L_g ”.
- Mass flow rate of oxidant “ \dot{m}_o ”.
- Radius of the throat (critical section) of de Laval nozzle R_t .

The variables feed a simplified chemical balance equation implemented in a computational algorithm with a regression rate calculation routine. The chemical equilibrium programmed generate values for the ratio of specific heats, value that if combined with other environmental quantities such as an external pressure and nozzle throat area (calculated from the throat diameter), allow the calculation of the characteristic speed of the gas “ c^* ” and the thrust coefficient “ C_F ” shown in Eq. (1) and Eq. (2), respectively.

$$c^* = \frac{\sqrt{\gamma R_g T_c / \gamma}}{\sqrt{\left[\frac{2}{\gamma + 1}\right]^{\frac{\gamma + 1}{\gamma - 1}}}} \quad (1)$$

$$C_F = \sqrt{\left(2 \frac{\gamma^2}{\gamma - 1} \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma + 1}{\gamma - 1}} \left(1 - \left(\frac{p_e}{(\dot{m}_o + \dot{m}_f) \frac{c^*}{A_t}}\right)^{\frac{\gamma - 1}{\gamma}}\right)\right)} + \frac{p_e - p_a}{(\dot{m}_o + \dot{m}_f) \frac{c^*}{A_t}} \quad (2)$$

The regression rate of the routine uses geometric relationships between the variables “ D_g ”, “ D_{in} ” and “ L_g ”, and Eq. (3) and Eq. (4) together with experimental coefficients (Bertoldi, 2007) to calculate the flow through the motor grain. From the characteristic speed of the gas “ c^* ”, the thrust coefficient “ C_F ”, the mass flow rate of the fuel “ \dot{m}_f ” and oxidant “ \dot{m}_o ”, it is possible to estimate the value of the thrust, as shown in Eq. (5).

$$\bar{r} = \frac{d_f - d_{in}}{2t_b} \quad (3)$$

$$d_f = \sqrt{d_i^2 - \frac{4\Delta m_f}{\pi L_g \rho_f}} \quad (4)$$

where in Eq. (3) and Eq. (4) t_b is the burning time, d_f is the fuel grain diameter after combustion, Δm_f is the fuel mass burned (difference between the mass before and after testing) and ρ_f is the fuel density.

$$F = c^* C_F (\dot{m}_o + \dot{m}_f) \quad (5)$$

Throughout the numerical optimization and post-processing procedures conducted after the final modifications of the rocket motor, some characteristics were obtained:

- Outside diameter of the propellant grain: 66.6 mm.
- Internal diameter of the propellant grain: 12.7 mm.
- Propellant grain length: 45 mm.

- Mass flow rate of oxidant: 150 g / s.
- Throat diameter (critical section) of the nozzle: 11 mm.

The post-processing led to an inner diameter of the fuel grain equal to 25 mm, and by experience from previous test benches; it was proved that the ignition system had better efficiency for this size of combustion port. The Propulsion Team also applied the internal ballistic algorithm combined with an empirical process in order to calibrate the injector, matching it to the required oxidant mass flow rate. The calibration process involved several tests with progressively increasing amounts of the injection orifices diameters until the ignition and the engine design requisites were mutually achieved. Listed below are the engine specifications calculated by the algorithm:

- Average thrust: 292.93 N.
- Average chamber pressure: 2.85 MPa.
- Average specific impulse: 233 s.
- Average O/F ratio: 6.9.
- Oxidant mass: 0.984 kg.
- Fuel Mass: 0.138 kg.
- Nozzle exit diameter: 20.3 mm.
- Nozzle expansion ratio: 3:39.

The values of oxidizer-to-fuel ratio (O/F ratio) were obtained and used in order to not generate large losses of specific impulse for the propellant studied, behaving similar to the Fig. 3 (Sutton, 2010).

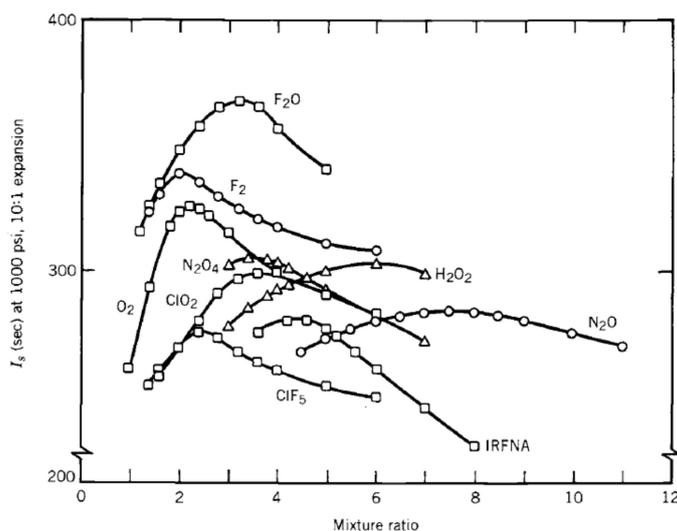


Figure 3. Specific impulse versus O/F (Sutton, 2010).

2.2 Mechanical design

Due to the goal of mass reduction and performance improvement of the motor, aluminum alloy 6061-O composed the injector and the post combustion chamber because of its high thermal conductivity and low density, while the steel AISI 304 was used as the material for the engine envelope due to their high specific strength. The sealing of combustion gases was performed by two Viton O-rings coupled to each cap. For the connection between the injector and the post chamber M5 bolts working as shear pins were used, according to the methodology of Pfeil (1977). Arranged radially, the bolts do not require precise grip, dispensing the necessity of a torque wrench, making the mounting and the exchange of the grain easier.

The injector has a Shower Head design, and sizing coefficient was based on the discharge methodology described by Sutton (2010) in which the oxidant vaporizes due to the pressure loss when flowing through the orifices, and as described before, it was also calibrated empirically to obtain the nominal mass flow rate of 150 g / s. Sutton (2010) reports that the greatest heat transfer occurs in the throat of the nozzle, while the after-chamber is subject only to radiation, therefore, it is feasible to use the aluminum alloy in the post-tube to minimize the mass of the combustion chamber. The expected heat dissipation was observed in many firing tests, and the materials withstood high temperatures.

2.3 Thermal design

During the combustion of the propellant inside the engine, an insulation stays positioned between the housing and the flow of hot gases, whose temperature may exceed 2273 K with a pressure of 6.9 MPa or higher (Kurokawa 2003). This phenomenon is amplified in the convergent section of the nozzle due to the increase of the flow velocity that enhances the heat transfer (Bartz, D. R., 1957). In order to prevent excessive heat transfer from the nozzle to the post-chamber cover, the chosen solution was to use a graphite nozzle. This material has a heat conduction ratio less than 24 W / m K (MatWeb, Graphite, Carbon, C) when compared to metals used in the manufacturing of the nozzles such as stainless steel, 200 W / m K (MatWeb, 304 Stainless Steel). Therefore, this also reduces the dry mass of the engine and the complexity of manufacture.

The rocket nozzle undergoes ablation and sublimation processes, the power dissipation throughout the graphite generates thermal, mechanical and chemical degradations, which are combined with a simultaneous removal of the surface of the material during the interaction with gases at high temperature and speed, this results in the thermal protection of the substrate (Kurokawa, 2003). The phenomenon is commonly applied to the thermal protection of combustion chambers of solid rocket engines with the goal of avoiding the need of using more sophisticated refrigeration systems (Thimoteo, 1986). In order to provide reliability to the system, it was decided to discard and replace the nozzle after testing, just in the case of erosion, the increase of the throat diameter, for instance.

2.4 Static tests

A pressure static test was necessary to ensure that the manufacturing and the design processes of the engine were sufficiently accurate. To perform it, a high pressure oil was applied to the chamber, pressurizing it (all outputs were sealed). This test simulates the pressurization of the chamber to verify if all the seals are working properly and if the materials present cracks. In the static test, the chamber was subjected to a pressure level of 15 MPa, which corresponds to 5.2 times the nominal pressure, and at this moment the oil began to leak from the post chamber o-rings. Therefore, the safety factor found was 5.2 to the internal pressure at room temperature.

3 BENCH DESIGN

The design of the bench meets three main guidelines: ergonomics, flexibility and safety. The bench, for research purposes should withstand several values of thrust to enable a reliable comparison between multiple engines, since it is the only piece that changes.

Based on these requirements and the guidelines presented by Barcelos (2012) proposed a bench composed of a support and a rail cart where the engine is fixed. The engine is fixed to the rail cart, which has four pillow blocks, and mounted on two linear guides connected to the support, this device acts as a horizontal thrust balance. In order to increase the convenience of mounting the support, the cart was designed to be lifted by two people with the engine already installed, after the assembly is secured on a concrete block clamped to the ground (Fig. 4).

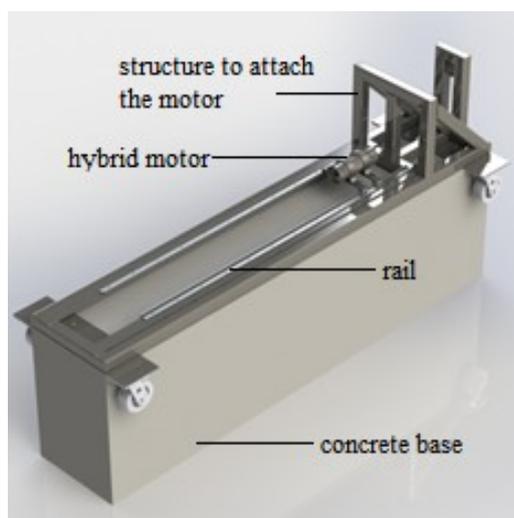


Figure 4. 3D diagram of the new workbench.

The current configuration of the bench allows testing motor of up to 300 mm outer diameter and 2,000 mm in total length and nominal thrust up to 3,500 N. The test bench is installed in the Chemical Propulsion Laboratory at the University of Brasilia and the facilities were built in order to avoid accidents. Between the test bench and the container

used as control room, there is a wall with two layers of water barrels in “L” configuration and 1.8 m of height. In case of explosion the rocket detaches from the rail and the oxidizer main valve is closed. This wall can protect all the staff and university buildings from eventual accidents. In parallel, the system has a Nitrogen purge whose goal is to stop the combustion in case of emergency or at the end of a test.

3.1 System power and acquisition

The oxidant supply system used a liquid nitrous oxide tank controlled by electro-pneumatic high-pressure valves, with a sensor to prevent reflux into the oxidizer tank.

To extinguish the flame of the combustion chamber, nitrogen gas is applied through an auxiliary line after the command to stop the nitrous oxide flow, extinguishing the flame due to lack of oxidant. This system works both for emergencies and to extinguish the flame of a test at a chosen time. The nitrogen extinguishes the flame instantly allowing the study of the grain at the moment that the oxidant was cut off, improving the regression rate measurements. Figure 5 shows a diagram of the electro-pneumatic system used in the bench. Through a load cell, it is possible to measure the thrust. With a pressure transducer in the engine chamber, the pressure is measured and these data is evaluated together with the engine performance in the project.

A key part of any experiment is the calibration of the instruments. The motor is mounted on the bench with all devices and known forces are imposed to the output of the nozzle. The magnitude of the forces are similar to the ones during the engine operation. The calibration of the load cell will take into account the deformations and backlash of the whole set. The pressure transducers were calibrated in the Laboratory Dynamic Metrology of the University of Brasilia.

Currently, the rocket bench has available two different acquisition systems (DAQ), the first is composed exclusively of analogical channels, manufactured by Lynx *Tecnologia Eletrônica*, while the second has digital ports and was manufactured by National Instruments, being frequently used in association. The calibration of the sensors related to the Lynx system which corresponds to the load cell, the pressure transducers and the thermocouples were described by Ishioka and Bertoldi (2015).

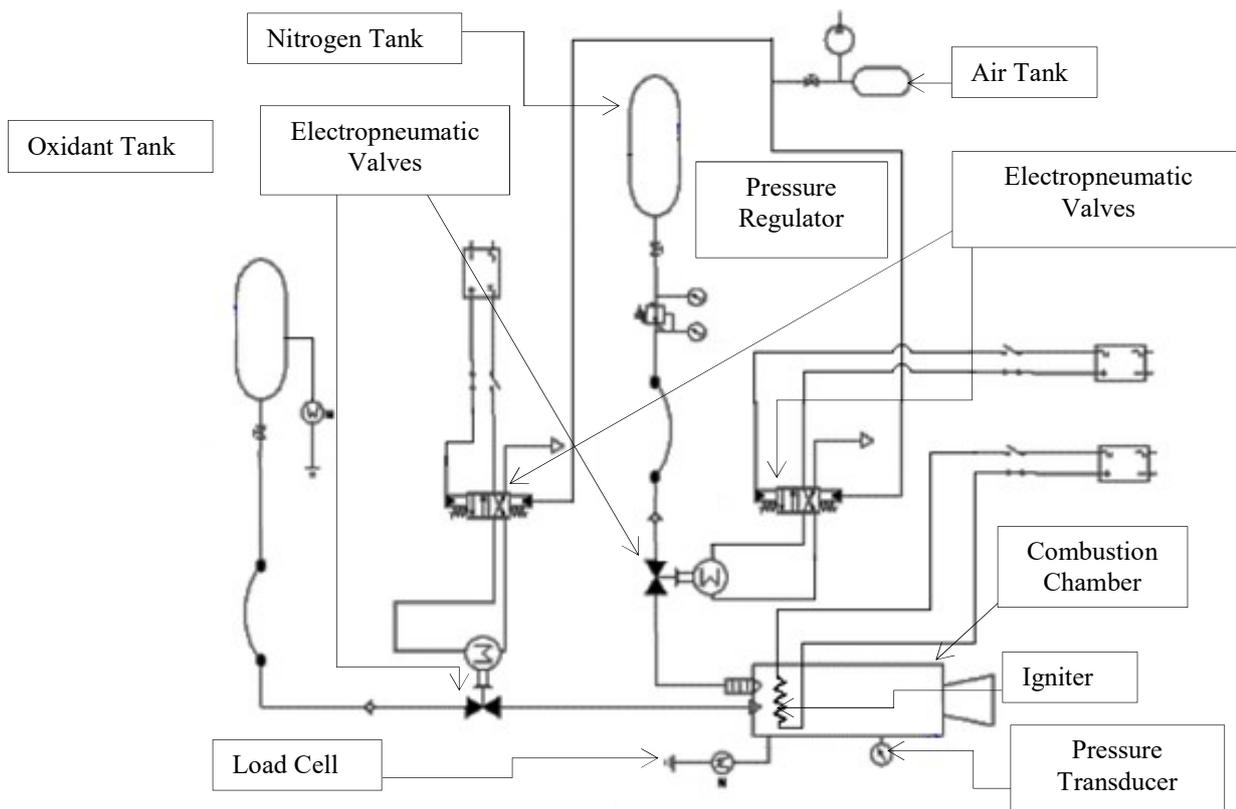


Figure 5. Scheme of the power and acquisition systems.

3.2 Ignition system

The ignition system for this specific sequence of testing is based on a solid fuel. In order to reduce costs in the static fires, the ignition was performed by a charge of potassium nitrate (KNO_3)/sucrose also known as *Rocket Candy*. For the LILE-2 qualification flying test, the ignition system was changed for the more energetic one based on black powder propellant. The table 1 shows the main parameters for the black powder solid ignition system.

Table 1. Main parameters of the ignition system.

Parameter	value	units
Initial combustion chamber pressure	1...100	kPa
Mass flow	2...29	g/s
Charge mass	23.5	g
Heat capacity	540	J/kg
Operation time (max)	3.4	s

4 EXPERIMENTAL RESULTS

After mounting the experimental apparatus, several firing tests were performed in the LILE-2 motor. In the Figure 7, the data of the first test is presented and it was intended to verify the operation of the rocket motor and demonstrate the operation of the ignition, power and acquisition systems of the bench. It may be noted that the experimental values differ from the nominal design values, however, this result is expected since the test was carried out previously to the calibration of the injector, what resulted in lower chamber pressure and thrust. At the left of Fig. 6, it is showed in detail the measurement devices: load cell to acquire the thrust and pressure transducers upstream and downstream (chamber pressure) of the injector plate. At the right of Fig. 6, it is showed the plume during the engine test. Using the mass variation from the method described in Bertoldi (2007), it could be estimated 2.1 mm / s as average rate of regression of solid fuel for this test.

Figure 7 shows the profile of the pressure in the chamber, the pressure in the oxidant line and thrust. Through the analysis of these two data, it was possible to infer that the sudden drop of the pressure in the combustion chamber after 5 seconds of burning was due to the sudden pressure drop in the oxidant line. These effects reflected in the time history of the thrust.



Figure 6. LILE-2 motor installed on the bench at the left, and its firing test at the right.

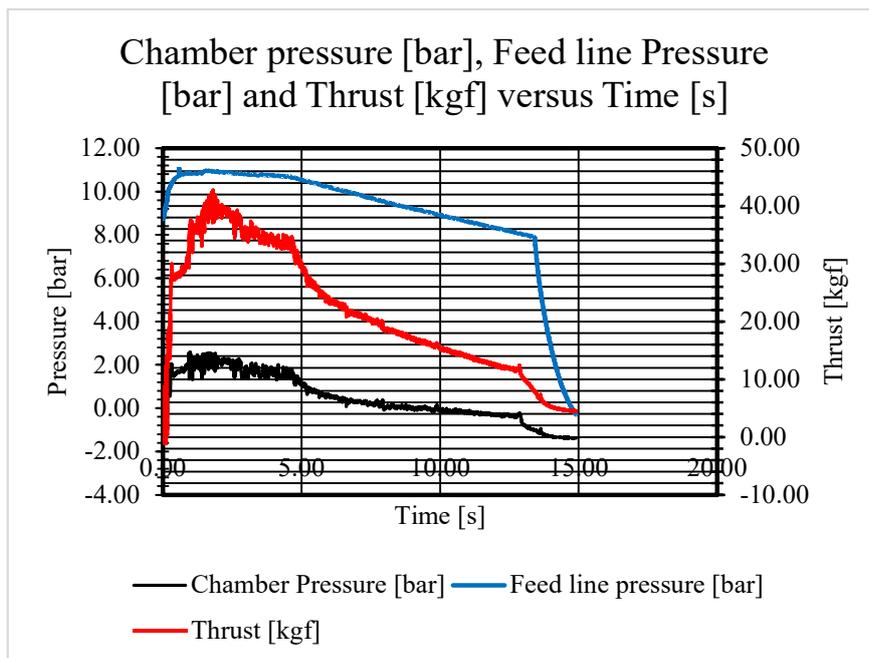


Figure 7. Chamber pressure [bar], Feed line Pressure [bar] and Thrust [kgf] versus Time [s].

Laboratory scale hybrid rocket motors with thrust interval of 100 N to 300 N are worldwide employed for studying the propulsive characteristics of different propellants. In this work, the pair propellant paraffin and nitrous oxide was chosen. In Brazil, the University of Brasilia is pioneer in the study of hybrid rocket motors working with different combinations of fuels and oxidizers, and under several levels of thrust, ranging from 100 N to 3,500 N.

In this work a small hybrid motor is tested only to validate the operation of the new workbench facility of the UnB Campus Gama. The test results show that the thrust level, the chamber pressure and the regression ratio are comparable to the ones of the main literature in the area. For instance, the paraffin regression ratio can change between 1.5 mm / s to 5 mm / s depending on the oxidizer mass flow, which is in agreement to the work of Bertoldi (2007), Karabeyoglu et all (2003), Karabeyoglu et all (2004). The average regression ratio measure in this work was 2.1 mm/s, a consistent value.

In order to evaluate the preliminary design, we used the methodology presented in the ballistic model to achieve the levels of chamber pressure, burning time, regression rate and thrust acquired in the bench test. The mean mass flow rate was the variable used to adapt the design to the results, and as expected, the mass flow rate achieved was 115.8 g/s, with mean pressure chamber of 1.96 MPa, 13 seconds of burning time, 2,5 mm/s of mean regression rate and mean thrust of 273 N. And this contributes to the uncertainty in the design of the injection system.

The levels of the pressure of the oxidizer line and of the combustion chamber are in accordance to the work published by Shynkarenko and Bertoldi (2015). The workbench, here validated, was also used to run tests of the engineering model of a hybrid motor with the same characteristics of the one in the SARA platform (IAE-Brazil), as described by the work of Andrianov et all (2015).

5 CONCLUSION

The experimental results show that the longer burning time and lower thrust and chamber pressure do not match with the estimated internal ballistic. This leads us to infer that the mass flow of nitrous oxide is lower than expected; a simple solution to this would be to increase the diameter of the orifices in the injector plate until the ballistic parameters were achieved. It is also worth mentioning that both the internal ballistics and gun model design considered the saturation pressure of nitrous oxide, approximately 5.65 MPa at room temperature, but the line pressure graph already starts with pressure below 5.0 MPa due to pressure drop in the pipelines, fittings and valves.

As a suggestion for future work, it is necessary to map the line pressure loss and to allow for re-pressurization profile of nitrous oxide in the tank so that a ballistic model and the gun design to be more accurate. Regarding the design of the experimental setup, the burning test and the data acquisition system integration with the instruments (pressure transducers and load cells) occurred properly, ensuring ergonomics, safety and accuracy.

The new bench developed for integrating the Laboratory of Chemical Propulsion from University of Brasilia allowed among other testing activities, the characterization of another hybrid motor, this one developed by undergraduate students with the support of the professors. The systems, motor and rocket, were both named Hermes whose flight model test is presented on the left of the Fig. 8. Such characterization was presented by Ishioka and

Bertoldi (2015), dealing complimentary on how the acquisition system implemented at the bench assisted the development of the avionics of the sounding rocket launched in 2015.

Therefore, it may be clear at this point that the bench project brought satisfactory results fulfilling its objectives, and will continue to provide a reliable platform for characterizing rocket motors with the specified constraints: chemical propulsive systems porting 300 mm of outlet diameter; 2,000 mm in total length, and thrust up to 3,500 N.



Figure 8. Hermes motor being submitted to the first firing test on the developed bench at the left, and the Hermes sounding rocket launched at the right (Ishioka and Bertoldi, 2015).

6. REFERENCES

- Andrianov, A., Shynkarenko, O., Bertoldi, A.E.M., Barcelos Júnior, M. D. N., Veras, C.A.G., 2015 Concept and design of the hybrid test-motor for development of a propulsive decelerator of SARA reentry capsule. In: 51st AIAA/SAE/ASEE Joint Propulsion Conference, Orlando. 51st AIAA/SAE/ASEE Joint Propulsion Conference. Reston: American Institute of Aeronautics and Astronautics.
- Bartz, D. R., 1957. A Simple Equation for Rapid Estimation of Rocket Nozzle Convective Heat Transfer Coefficient, *Jet Propulsion*
- Bertoldi, A. E., 2007. Experimental Investigations of burning of Paraffin and Nitrous Oxide in Hybrid Rocket Engines, Master Dissertation (in Portuguese). University of Brasília, Brazil.
- Ishioka, I. S. K., Bertoldi, A. E. M., 2015. Implementação de Sistema de Aquisição para Teste Estático de Motor Foguete Propelente Híbrido, 21^o Congresso de Iniciação Científica da UnB, Brasília, DF, Brazil.
- Karabeyoglu, A., Ziliac, G., Cantwell, B. J., Dezilwa, S., Castellucci, P., 2004, "Scale-up Tests of High Regression Rate Paraffin-Based Hybrid Rocket Fuels", *Journal of Propulsion and Power*, v.20, n.6, p. 1037-1045
- Karabeyoglu, A., Ziliac, G., Castellucci, P., Urbanczyk, P., Stevens, J., Inalhan, G., Cantwell, B. J., 2003, "Development of High-Burning-Rate Hybrid-Rocket-Fuel Flight Demonstrators, 39th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Huntsville, AL, USA.
- Karabeyoglu, M. A., 2008. Hybrid Rocket Propulsion for Future Space Launch. Aero/Astro 50th Year Anniversary, Stanford University.
- Kurokawa, F. Y., 2003. Study hybrid analytical / numerical diffusion equation in bidimensional solids with ablative thermal protection, Master Dissertation, UNESP.
- Manuel N. D. B. Jr. Dr, Erlan R. S. C, Pedro, L. K. C., 2012. Development and design of bench for static testing of rocket propulsion engines, IV Encontro de Ciência e Tecnologia do Gama.
- MatWeb, Material Property Data. 304 Stainless Steel, 22 Jan 2013 <<http://www.matweb.com/search/DataSheet.aspx?MatGUID=abc4415b0f8b490387e3c922237098da&ckck>>
- MatWeb, Material Property Data. Graphite, Carbon, C, CAS Number: 7440-44-0, 20 Jan 2013 <<http://www.matweb.com/search/DataSheet.aspx?MatGUID=3f64b985402445c0a5af911135909344>>
- MIL-STD-1522A, 1984. Military standard standard general requirements for safe design and operation of pressurized missile and space systems. Department of air force. Washington, D.C.
- Pfeil, W., Estruturas em Aço, Livros Técnicos S.A., Rio de Janeiro .1977
- Shynkarenko, O., Bertoldi, A.E.M., 2014 Preliminary Research of the Hybrid Motor Properties for the Reentry Platform. *Journal of Problems of High-Temperature Engineering*, v. 1, p. 156-164.
- Sutton G. P., Biblarz O., 2010. *Rocket Propulsion Elements*. Wiley, New Jersey Eighth Edition.
- Veras, C. A. G., 2011. Hybrid Rocket Propulsion Research Activities in Brazil: Past, Present and Future. Third International Conference Space Technologies, April 20-22, 2011, Dnepropetrovsk, Ukraine.
- Veras, C.A.G., da Cás, P.L.K., Vilanova, C.Q., Borges, G., Menegás, H.M., Ishihara, J.Y., 2010. Thrust Modulation on a Paraffin Based Hybrid Rocket Motor, 13th Brazilian Congress of Thermal Sciences and Engineering, Uberlandia, MG, Brazil, December 05-10.

Vol. 27 , No. 1, Jan., 1957 Kaled Da Cás, P.L.K., Vilanova, C.Q., Manuel N. D. B. Jr., Veras, C.A.G. . An Optimized Hybrid Rocket Motor for the SARA Platform. J. Aerosp. Technol. Manag., São José dos Campos, Vol.4, No 3, pp. 317-330, Jul.-Sep., 2012 doi: 10.5028/jatm.2012.04032312

7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.