DEVELOPMENT OF EXPERIMENTAL FIRING TEST STAND TO INVESTIGATION AND STUDY THE LIQUID ROCKET ENGINE CHARACTERISTICS

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Abstract. *The main aim of this work is to present the specification of an experimental firing test stand of liquid rocket engine (LRE) and develop a program for control and acquisition data providing conditions to rocket engine with thrust of 50 to 100 kgf works in agreement with parameters of design. It's proposed a methodology for execution of laboratory work using resources of information technology, which will allow the automatic and remote functioning of the test stand, and it will permit to the users to do the inputs necessaries to realization of tests with safety and accuracy measurements for attainment of reliable results. The control of mass flow rates of propellant by pressure regulators and others valves of system, as well as the data acquisition of test stand shall be done automatically through LabVIEW software. The test stand program shall be readable, scalable and maintainable code. The test stand design and its development represent the state of art of experimental apparatus in the knowledge of LRE.*

Keywords*: Test stand, liquid rocket engine, control, acquisition data.*

1. INTRODUCTION

The Brazilian Space Agency (AEB) through of the PNAE - National Plan of Space Activities (2005) has invested in the formation of specialists in the technology of calculation, design and construction of liquid rocket engine (LRE). In the next version of Brazilian Vehicle launcher of Satellite (VLS) is scheduled, in principle, the utilization the LRE only in the upper stages but in the future versions the LRE will be employed in others stages of the vehicle.

The advantages of LRE in relation of the solid propellant rocket motor, justify the investment in this area. Among the advantages of LRE it can highlight the long time of working, the control of thrust and the higher specific impulse.

The liquid rockets engines are subjected to tests in installations known as test stands before to be put into operation. The test stands are complexes of facilities equipped with devices providing an implementation of LRE tests in the order to determine its parameters and performance.

In September 17th, 2005, the Institute of Aeronautics and Space (IAE) performed the first firing test of a liquid rocket engine of 5 kN of thrust (called as L5 engine), the tests were carried out in a test stand located at Liquid Propulsion Laboratory (LPL) in São José dos Campos, which has capacity to test engines up to 20 kN.

The L5 engine was designed for operating with liquid oxygen (LOX) and kerosene but in the preliminary phase of the tests it has been used ethyl alcohol as fuel. The injectors head is constituted of bipropellant centrifugal liquid injectors of which a line of holes in the periphery of fire bottom that permit the formation internally of a film cooling.

Currently the IAE is working, in two new projects in liquid propulsion field. L15 engine is a bipropellant liquid rocket engine of 15 kN of thrust that operates with liquid oxygen and ethyl alcohol, which will be used in sounding rocket called as VS-15. The other project in development is called L75; it is a bipropellant LRE of 75 kN of thrust and will operate with a turbopump feeding system using the propellants: liquid oxygen and kerosene.

This work has originated of two master's dissertations of Aerospace Engineering course of liquid propulsion area of Aeronautics Institute of Technology (ITA). The first one approached the specification of test stand, design of LRE, and methodology of test (Alves, 2008). The second one approached the development of a program for control and acquisition data of the test stand (Andrade, 2008).

The IAE decided to build this test stand that is in final phase of assembly. This installation is scheduled to operation in November, 2009, it will be used as educational tool in the formation of new groups of master degree course of Aeronautics Institute of Technology (ITA), training of technical personnel of IAE and development of LRE researches and others related areas.

The apparatus in development will allow basically the realization of laboratories work to verify the influence of mass flow rate (object of this work) and of the expansion ratio in the thrust of an LRE. With smalls modifications in the thrust chamber it will be possible to carry out another laboratory work about heat flow along of engine. Using a control and acquisition automatic system the user will operate remotely the engine and make measurements of several parameters like: pressures, temperatures, mass flow rates as well as thrust force**.**

2. THEORETICAL BASEMENT OF LIQUID ROCKET ENGINE

The LRE consists basically of one thrust chamber, tanks to store the propellants, a feed system to force the propellants into the thrust chamber, a power source to supply the energy for the feed system, piping to transfer the liquids, a structure to transmit the thrust, and control devices to initiate and regulate the propellant flow and this manner the thrust (Sutton, 2001). The thrust chamber, in turn, is the main part of a rocket engine (Sutton, 2001), it is formed usually by injector head, combustion chamber, nozzle, cooling Jacket and ignition system according to Fig. 1.

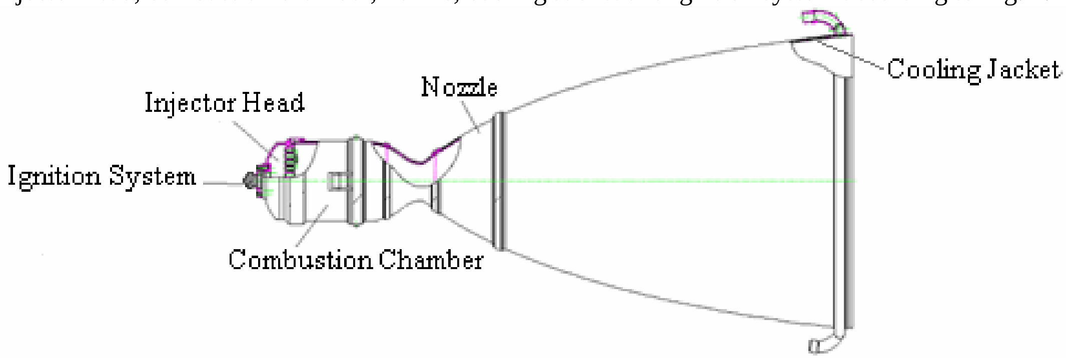

Figure 1: Thrust chamber

The injector head consists of injectors set distributed along surface of a plate placed at inlet of combustion chamber and a set of ducts that guarantees a homogeneous distribution of propellants. The injectors are the elements more important of thrust chamber because determine the behavior of propellants in the combustion chamber. It injects and atomizes the propellants into the combustion chamber, mixing homogeneously and in ratios well defined the fuel and the oxidizer for it's vaporized and burned quickly.

The injectors are classified in centrifugal or jet. They can be mono or bipropellant, in case of two propellants, for a better homogenization of mixture, it can be used an unique coaxial centrifugal injector.

The combustion chamber is the part of thrust chamber in which the combustion of propellants occurs at high pressures and temperatures. The process of combustion can be characterized in three zones (Kessaev, 2006): 1- Gasification zone (warming-up, evaporation), 2- Burning zone, and 3- Combustion product mixing zone. Internal cooling of combustion chamber is made to protect the inner shell from contact with the high temperature gases. They can be of two types: by wall layer that is constituted by a flow of combustion products with lesser temperature of burning along wall; and by wall screen formed by the liquid fuel film.

The hot gases of combustion are accelerated since the stagnation until to transonic velocity in the throat reaching supersonic velocity in the exit of nozzle (Barrère, 1960).

There are different types of nozzles, they are: conical nozzle, contoured nozzle and ring nozzle. The conical nozzles are simply and relatively easy to manufacture but are not the most efficient in the terms of thrust by a given length.

The type of nozzle choose in this work was the conical nozzle, firstly due its simplicity and facility of manufacture.

The basic objective of cooling jacket in thrust chamber is to prevent that its walls becomes enough hot, so they will not be able to withstand the imposed by loads thermal and stresses, thus leading the engine to fail. Most materials of walls lose strength and become weaker when temperature is increased. Cooling thus reduces the wall temperatures to an acceptable value (Sutton, 2001). The regenerative cooling is carried out by cooling jacket around the thrust chamber and circulating one of the liquid propellants through it before it is fed to the injector head.

The propellants are combined inside combustion chamber where they react chemically to form hot gases which are then accelerated and ejected at high velocity through nozzle (Huzel, 1992).

The equation of thrust in atmospheric conditions, as shown in the Fig. 2, it is given by:

$$F_H = \dot{m} \cdot W_a + A_a \left(P_a - P_H \right) \tag{1}$$

Where A_a is outlet area of nozzle, P_a is outlet static pressure of nozzle and P_H is the ambient pressure. This equation show a balance between the created forces due the mass ejected of rocket and the force due the effects of pressure in the exit of nozzle. In space applications the ambient pressure is considered zero (vacuum).

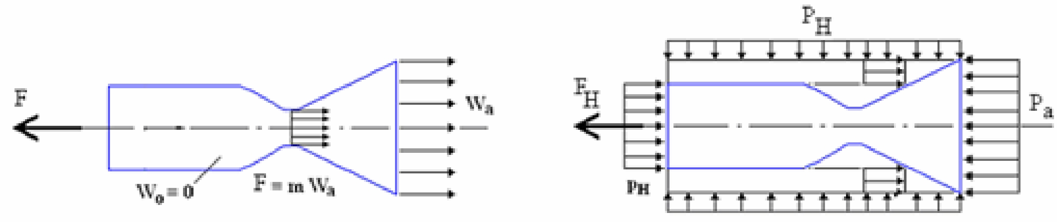

Figure 2: Thrust in the atmospheric conditions.

The specific impulse I_{sp} is the main measurement of performance of LRE. It is used in comparison among propellants, combination of propellants and performance of LRE. The I_{sp} can be calculated of two ways:

- Experimentally, from measuring of thrust (*F*) and the mass flow rate (*m*) of propellant according to equation (2) and from thermodynamics properties of propellants for a given expansion ratio P_a / P_{Ch}, according equation (3):

$$I_{sp} = \frac{F}{\dot{m}} = W_a . \frac{A_a (P_a - P_H)}{\dot{m}} \tag{2}$$

$$I_{sp} = \sqrt{\frac{2kRT_{Ch}}{(k-1)} \left[1 - \left(\frac{P_a}{P_{Ch}} \right)^{\frac{k-1}{k}} \right]} \tag{3}$$

The equation (2) also shows that the I_{sp} decreases with the increase of atmospheric pressure and is directly proportional to the thrust. The equation (3) shows that when the LRE is in an environment of vacuum with value of P_a tending to zero, the value of I_{sp} independent of value of internal pressure chamber.

The characteristic velocity C^* is a figure of thermo chemical merit for a particular propellant and may be considered an indicative of the combustion efficiency. It can be calculated of two ways:

- Experimentally through from measuring of chamber pressure (P_{Ch}), area of critical section (A_{Cr}) and mass flow rate (m point) according to equation (4) and from the thermodynamics properties of propellants used according to equation (5):

$$C^* = \frac{P_{Ch} \cdot A_{Cr}}{\dot{m}} \tag{4}$$

$$C^* = \frac{\sqrt{R \cdot T_{Ch}}}{\left(\frac{2}{k+1} \right)^{\frac{1}{k-1}} \cdot \sqrt{\frac{2k}{k+1}}} \tag{5}$$

The value of C* calculated empirically considers the losses friction and the movement of the gas in the throat. These losses depend directly of the profile of the nozzle. Where: R - Gas constant in (J/Kg.K), T_{Ch} - Temperature of combustion gases in chamber in (K) and k - adiabatic exponent.

3. METHODOLY OF LABORATORY WORK

The experimental test stand was designed initially to carry out firing and cold tests of liquid propellant rocket engine using a pressurized feed system. The liquid rocket engine will be worked with ethyl alcohol (C_2H_5OH) like fuel and gaseous oxygen like oxidizer.

The cooling of combustion chamber will be carried out with water. The pressurization of fuel tank and of the pilot lines that feed the pressures regulators, as well as the cleaning (blowing) of fuel line will be made with gaseous nitrogen (GN_2) comes from pressurized cylinders of 200 bar.

The test stand is a test station that allows tests of rocket engines in different regimes of operation by the variation of test conditions as chamber pressures, mass flow rates, and burning time. It offers measurements of several physical variables associated with these regimes.

The test stand will be controlled automatically by a computer (PC) that will allow the realization of measurements simultaneous during the working of rocket engine, allowing so remote control and more safety to user.

The choice of propellant (ethyl alcohol and gaseous oxygen) was made based on requirements as low cost, ease of acquisition, and non toxic product.

The tests will be carried out in four different regimes of operation with constant mixture ratio (k_m) - ratio between the mass flow rate of oxidizer and mass flow rate of fuel. The change of regimes will be obtained by variation of pressures in feeding lines of propellant, mass flow rates and chamber pressures. The burn time also will be changed and it will be limited only by size of fuel and oxidizer tanks. The number of regimes of operation can be enlarged calibrating the system with additional values of feed lines pressures and chamber pressures.

The tests will be realized sequentially according to the regimes of operation pre-defined. The system also will allow to user carry out one only regime of operation through of choice of one specific regime among available four options.

The control system will work basically in three different conditions: set up, operation and shut down, being that operation condition subdivided in starting, test, wait and finishing.

The test is initiated with actions of opening and closing synchronized of feed line valves to start the gas-dynamic igniter and then to give conditions to engine runs. During the burning of engine, the mixture ratio is kept constant for control of pressures in propellant lines by automatic pressure regulators (PID system). Initially the pressures referent to mass flow rates (fuel and oxidizer) are obtained by calculations but verified experimentally by tests.

4. DEVELOPMENT OF TEST STAND INSTALLATION

The main requirements of test stand to be developed are: propellants will be ethyl alcohol and gas oxygen, capacity of generate a 50 to 100 kgf range thrust, constant mixture ratio (k_m) for maximum specific impulse, 4 regimes of operation of 8, 10, 12 and 15 bar of pressure chamber, duration of each regime of operation equal to 10 seconds, constant the mass flow rate using pressure regulators in the feed lines of fuel and oxidizer, gas dynamic igniter to multiples ignitions, cooling jacket with water, control and acquisition of data automatic, safety system automatic by program. Considering the mixture ratio k_m equal 1,6 to maximum specific impulse, the values of mass flow rates of propellants of the combustion chamber and theirs respective thrusts for four regimes of operation were calculated and the results are shown in Tab.1.

Table 1. Pressures in the combustion chamber (P_{Ch}), mass flow rates ($\dot{m}_O, \dot{m}_F$) and thrusts (F_H) values.

Regimes	P_{Ch} (bar)	$\dot{m}_O$ (kg/s)	$\dot{m}_F$ (kg/s)	F_H (kgf)
1º	8	0,200	0,125	56,05
2º	10	0,250	0,157	70,22
3º	12	0,301	0,188	84,43
4º	15	0,376	0,235	105,78

In Fig. 3 it is shown the AutoCAD general drawing in cut of thrust chamber where it can be seen the ignition system (detail 1) and in the detail 2 the mechanical interface of the engine with the frame of the test stand.

The injectors head will be made of stainless steel except the fire bottom (detail 12) and duct of igniter (detail 7) which will be made of cooper.

The combustion chamber will be made all of stainless steel. On the inner shell (detail 6) there will be milling ribs, that begin in cylindrical part and finish before the throat, then till the end, the cooling jacket is constituted of double wall shell, without ribs. Also it can be seen the inlet and outlet of the cooling system in the details 15 and 4 of general drawing.

As it can be seen in the Fig. 3, the nozzle is segmented in parts that are removed during the laboratory work that configuration make possible to verify the influence of expansion ratio in the thrust, thus three conditions of expansion in the nozzle can be tested: under expanded, over expanded and adapted. In case this work, the tests to determination of LRE thrust characteristics will be carried out with only the three segments (details 16, 17 and 18 of general drawing) that corresponding to adapted nozzle to sea level.

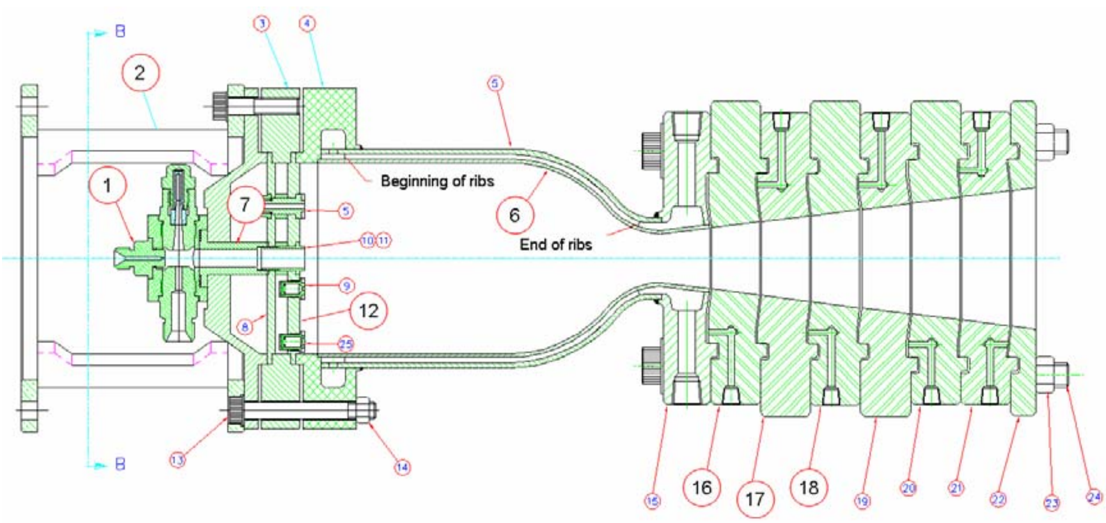

Figure 3: General drawing in longitudinal cut of thrust chamber.

The frame of bench is constituted the following parts shown in the self-explained Fig. 4. Where 1) load cell (measurement the thrust force), 2) Air spring (pneumatic spring), 3) Support of fixation the engine into the frame, 4) Rocket engine, 5) Balancim, 6) Dampers, 7) Body and 8 and 9) Counterweights (5 and 10 kg).

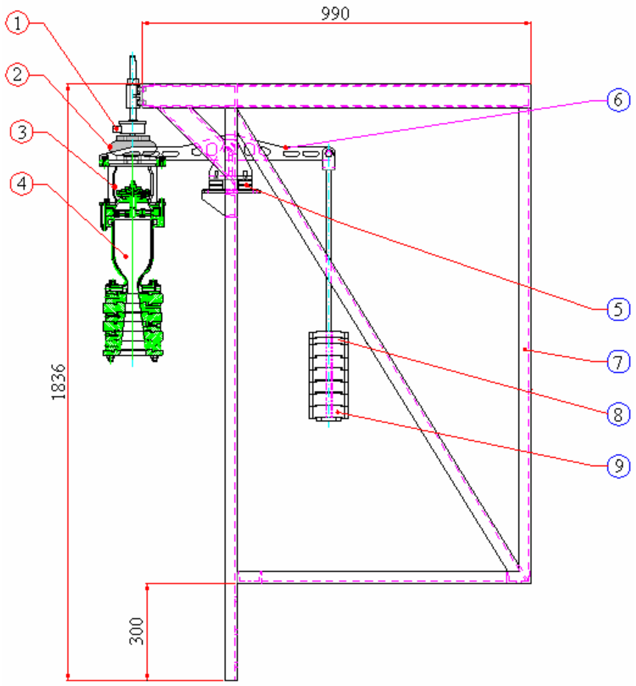

Figure 4: Lateral view of test stand design (engine in longitudinal cut).

The feed system is constituted of an hydropneumatic installation illustrated in Fig. 5, composed of piping lines, a series of valves, provisions for filling and removing (draining and flushing) the liquid propellants, and control devices to initiate, stop, and regulate their flow and operation.

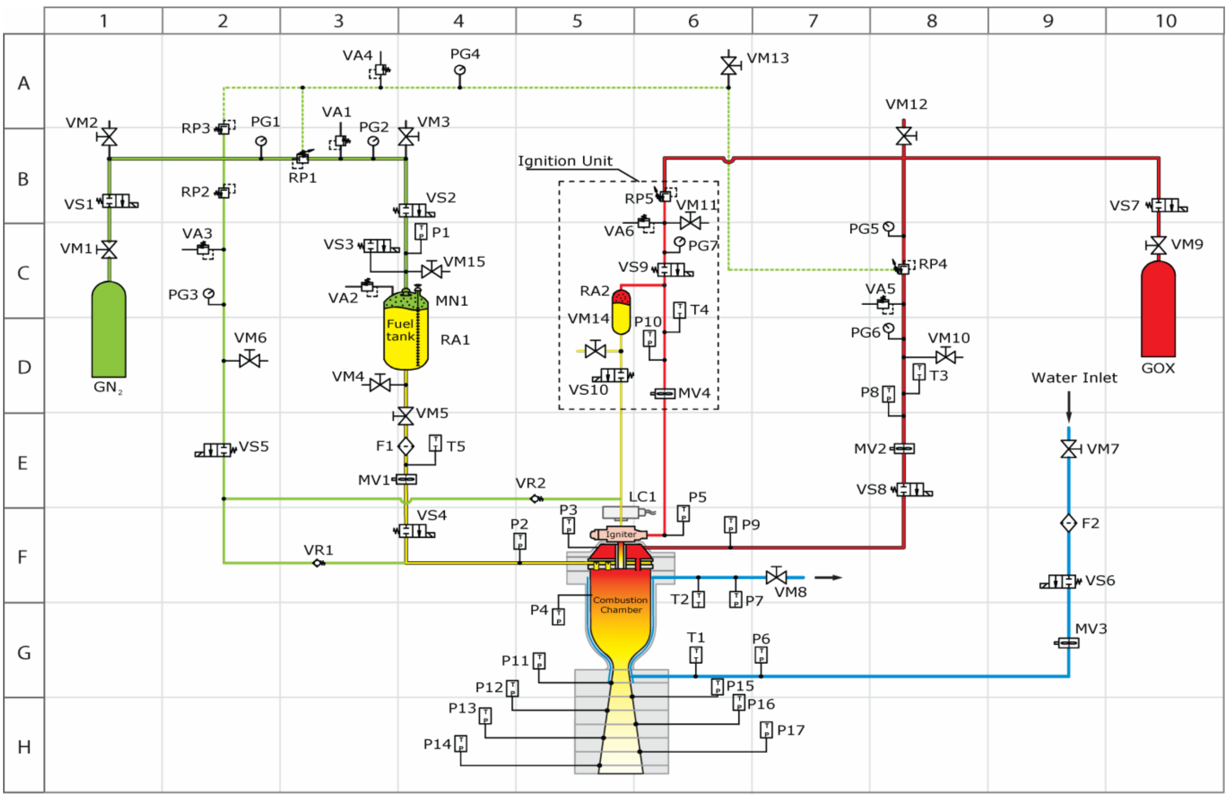

Figure 5: Hydropneumatic scheme.

The GOX from cylinder pass by pressure regulator where its pressure is reduced and goes to engine when electric valves are opened. Part of GOX is used in the ignition unit. The GN2 from cylinder is reduced by pressure regulator and pressurize the fuel tank for feed the engine. The scheme show also water inlet in the throat region and goes out from mixing head. The engine shown in the fig. 5 gets sensors of temperature and pressure, and cell load (LC1) to measure thrust.

The layout of the test complex shown in Fig. 6 gives an overview of arrangement and equipments of the control and data acquisition system. The interface between the test stand and the control room will be carry out by signal transmission cables represented by the black dotted line in fig. 6. As well as the propellant and the pressurization gas will be located in the three separated bays, the engine rocket will be installed in the frame of test stand. The Figure 6 presents also the control room that besides to protect the personnel against a possible explosion of the combustion chamber or tanks it includes mainly equipments of controlling, data acquisition and the program developed.

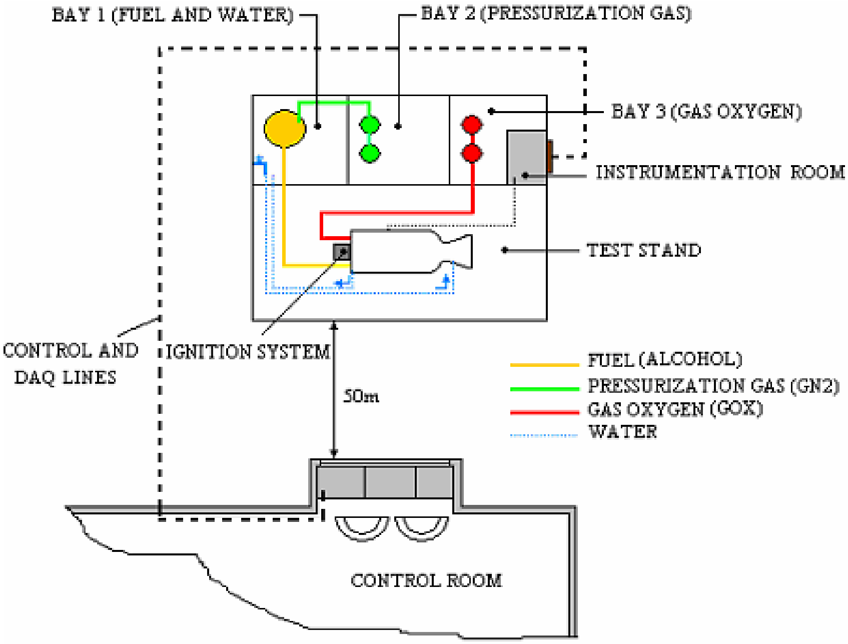

Figure 6: Layout of test complex.

5. METHODOLY AND DEVELOPMENT OF PROGRAM

The program developed for the control and data acquisition of test stand of LRE used the software LabView due to its friendly interface with the user and the possibility of be readable, scalable and maintainable code.

The development of the program cited above became possible by use of a development methodology well defined. For such development was carried out the following procedures of phases showed in the diagram of the fig. 7:

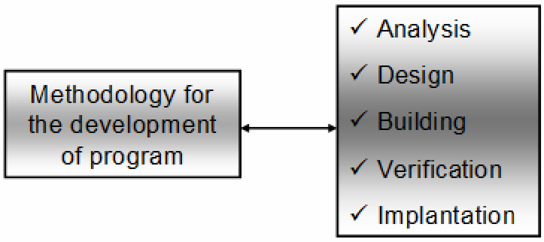

Figure 7: Phases of the methodology for the development of program.

5.1. Analysis

In this phase was done the investigation of the necessary data for the understanding of the design requirements. It was developed and elaborated the hydropneumatic scheme with the schedule of all its activities since the activation until the shutdown of the test stand. Based on hydropneumatic scheme shown in fig. 6 and the sequencing of the activities were prepared the states machine according Shaw (2003), with the purpose of supply and focus in the development of the program. The fig. 8 shows the state machine of the hydropneumatic scheme of test stand.

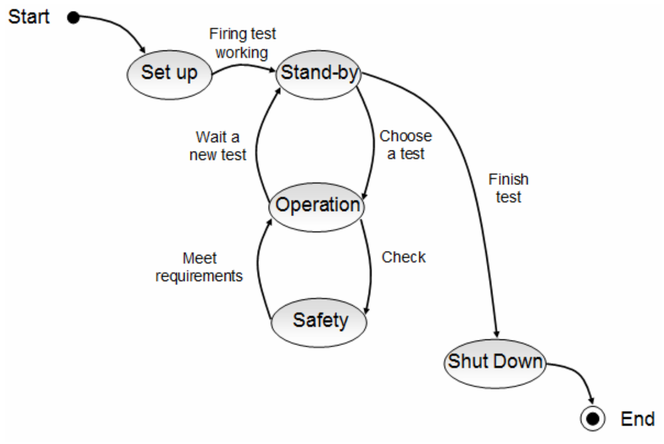

Figure 8: Test Stand State Diagram.

5.2. Design

In this phase was described the interface that the program developed has with the user and the infra-structure available to meets the functioning of the LRE and installation of the hydropneumatic scheme, according it was shown in fig. 6.

5.3. Building

In phase of building there was the interpretation of performed requirements resulting in development of LabView codification. All the codification sequence was made in modular way and scalable, and the comments inserted inside of the program itself. The next figures show some screens of developed program to control of the test stand.

The figure 9 shows the first screen of the program with its guides. The screen of guide called “Gravação” allow to the user:

- To choose the name and the folder where the acquisition data of test will be save;
- To monitor and save the generated data of sensors of test stand;
- To finish the check of sensors when they are being monitored;
- To determine what is the time of countdown of test.

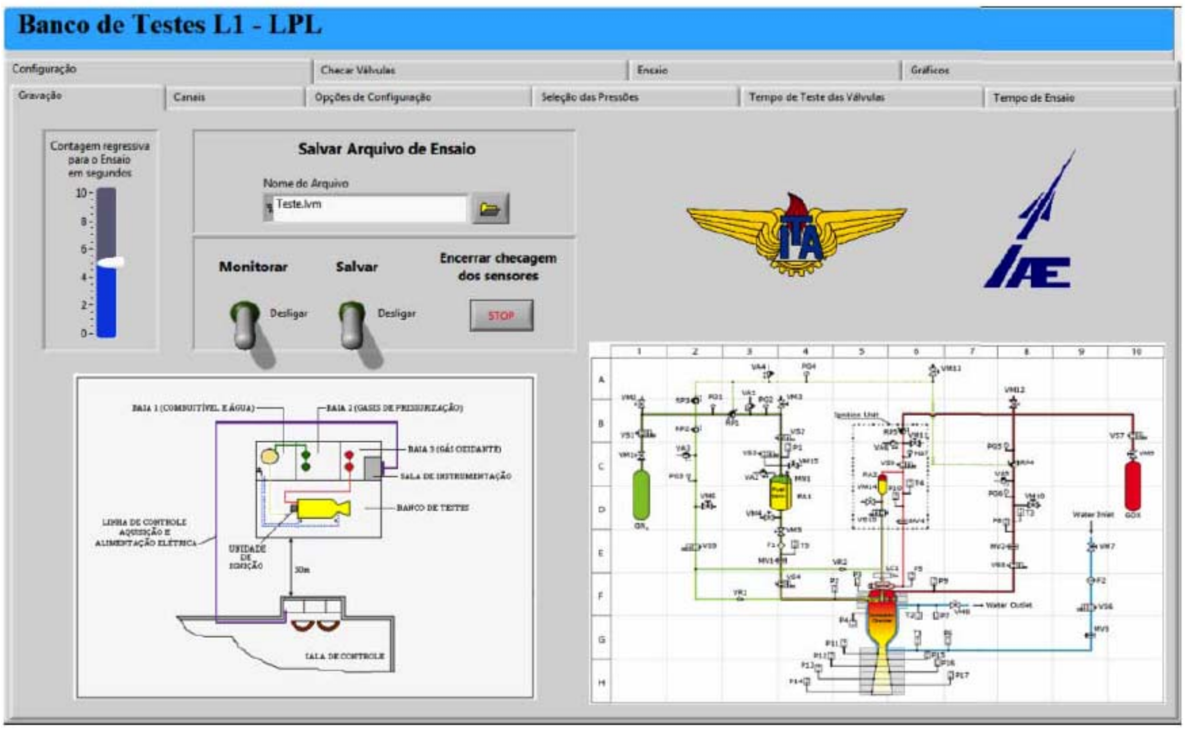

Figure 9: Initial screen of interface with user.

The figure 10 shows the screen of guide “Canais” where the user can choose the type of configuration like adjust the channels of the valves or keep the default.

Figure 10: Screen of guide “Canais”.

The figure 11 shows the screen of guide “Seleção das Pressões” where it is shown to user, besides others options, the pressures of combustion chamber available to test stand.

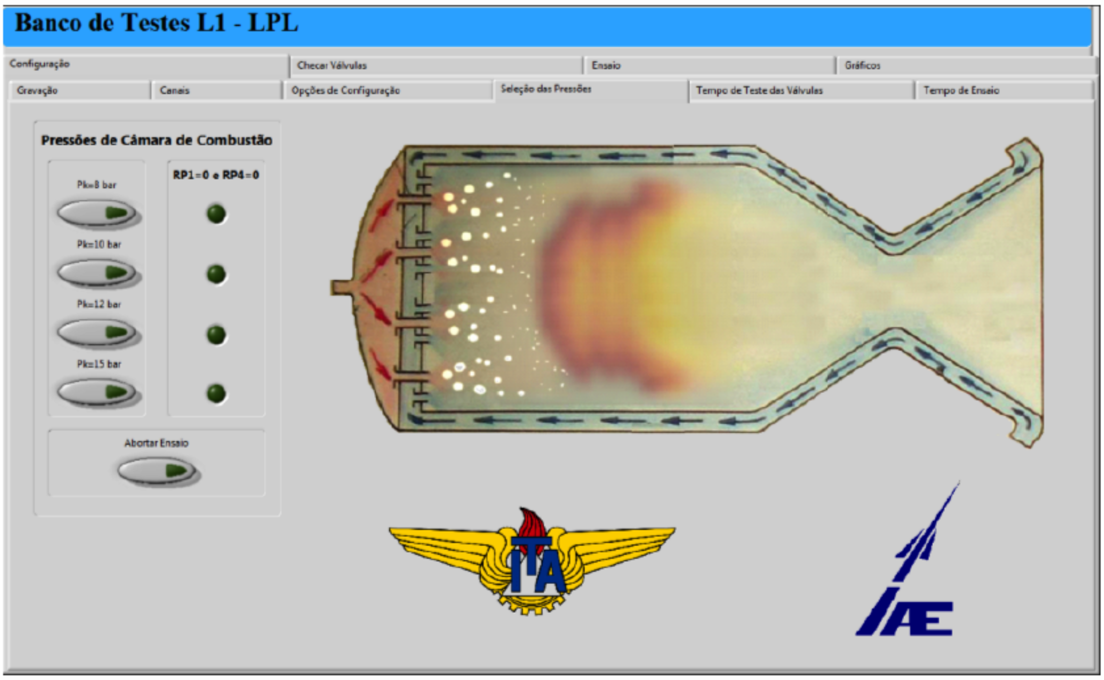

Figure 11: Screen of guide “Seleção das Pressões”.

The figure 12 shows the guide screen “Ensaio” where the user can perform and observe others options as a clock of test, a clock with countdown to the test, the pressures of the combustion chamber carried out in the moment of test. The visual alert of valves that are commented, the values of physical amounts recorded by sensors and the visual alert of automatic depressurization of fuel and oxidizer tanks when the internal pressure exceed the pre-established value.

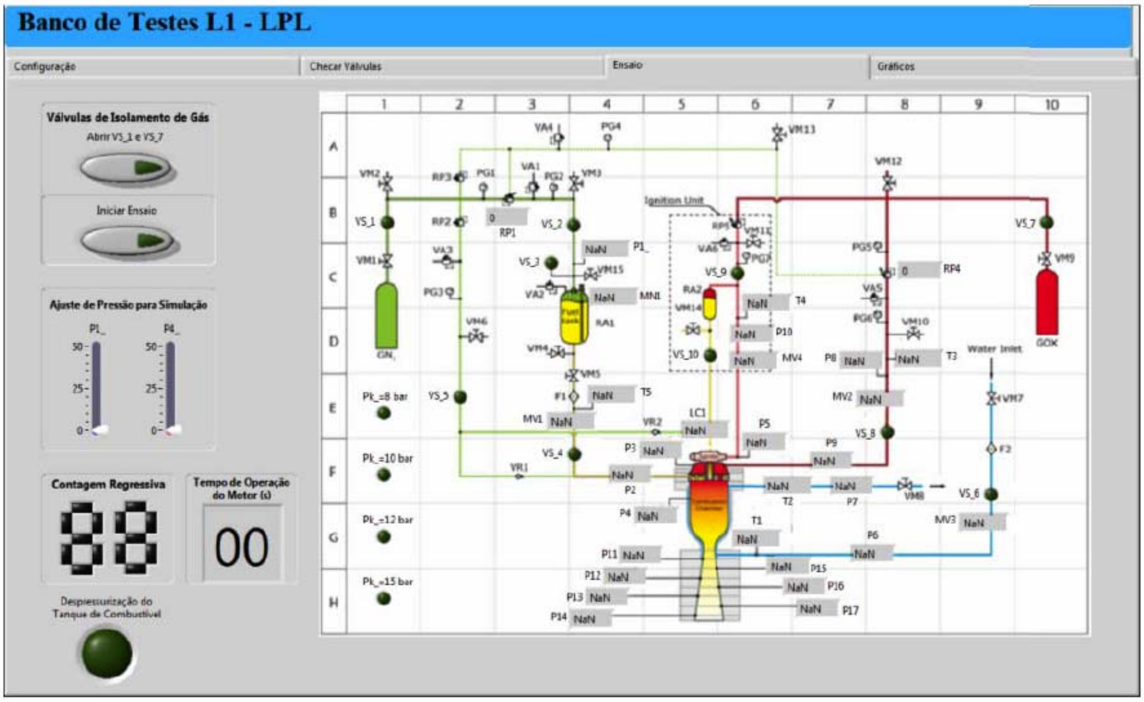

Figure 12: Screen of guide “Ensaio”.

5.4. Verification

This phase allow to identify and correct the existent failures in the program. For that such tests were performed:

- Software function test: where it can verify if all requirements were contemplated in the codification.
- Black box test: test the functionality of software and interaction with user.
- White box test: where the source code was tested in detail and all transitions of program verified.
- Integration test: where was tested the architecture of program and its communication with external interface.

5.4.1 Description of test

The objective of test was a simulation of test conditions through the computer in ambient Windows used a National Instruments data acquisition device. To simulate the open and close of the solenoid valves was used a panel of hydropneumatic scheme of test stand with Led’s that represented these valves. These Led’s turn on/turn off in determinated time representing the open/close of solenoid valves during the tests. To verify the data acquisition was used a device called DAQ-Acessory that supplies a square wave as analogical input and that was shown and stored by program. The figure 13 shows a function of square wave acquired by program.

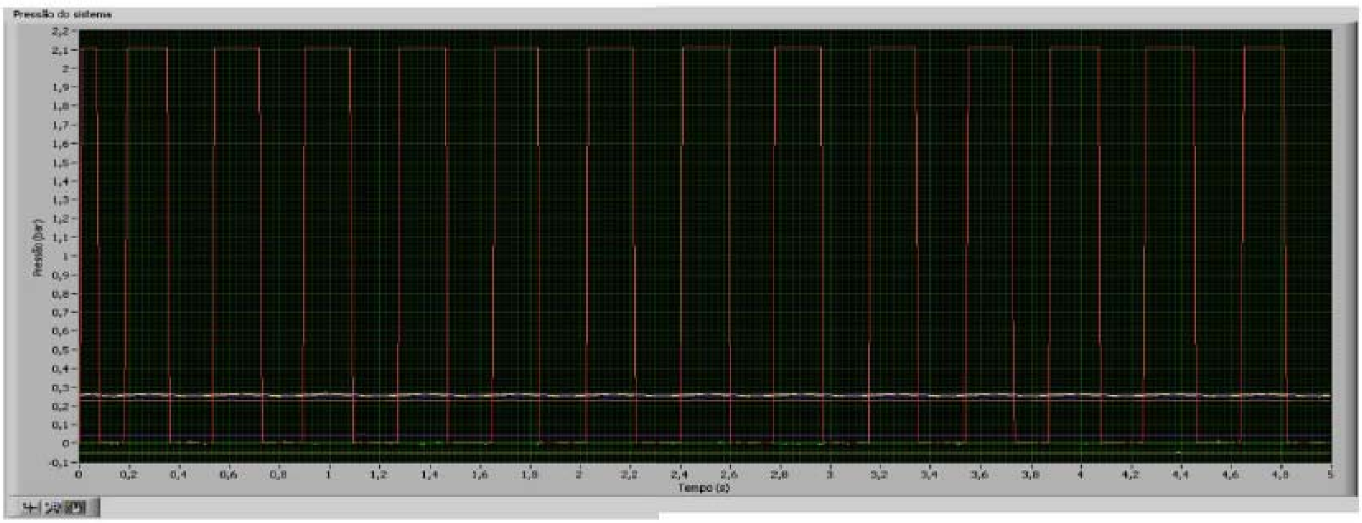

Figure 13: Graphic presents the data acquisition done by program.

5.5. Implantation

In this phase was defined the position of the control hardware of the test stand in control room of Liquid Propulsion Laboratory (see figure 06) and also was determined the level of responsibility of each operator during the test according to the standards of IAE.

At this standard is required a IAE qualified professional to be the test supervisor and manages the operations in the test stand.

6. CONCLUSION

This work presented the specification of an experimental firing test stand of liquid rocket engine (LRE) and the apparatus to its development for the realization of laboratories work. From design of hydropneumatic scheme and LRE led to the development of program for control and acquisition data giving conditions to engine works in agreement with parameters of design.

All the phases of this project were done with two major aims, first the excellence required in the space engineering field and the second, the state of the art of several engineering fields like electric, mechanic, thermodynamic, heat transfer, propulsion, combustion, and so on. These aims result in higher knowledge and aggregate value to development and investigation of LRE.

7. ACKNOWLEDGEMENTS

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9. RESPONSIBILITY NOTICE

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