Small Liquid Propellant Rocket Engine

Design, Build and Test

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December 2016

Abstract

The present document reflects the work developed in the S-SHE project, at Omnidea Lda. It was intended to design, build and test a small liquid rocket engine. The prototype should be able to produce 25N of thrust. This project aims to study the stability of the liquid engine with regenerative cooling and external pressurization, and the feasibility of the self-pressurized system. Therefore, the system should be flexible enough to allow two operation modes: external and auto pressurization. It is intended to have a low cost test stand and as simple as possible. Further objectives of this project are having a repeatable ignition, injection in gaseous phase and building a simple injector.

Keywords: Small liquid rocket engine, Self-pressurization, Regenerative cooling, gaseous injection, Repeatable ignition.

I. INTRODUCTION

There is a constant need to make launcher systems lighter and less complicated. Traditional feed systems are complex and heavy, and they consist mainly two types: turbopumps and gaspressurized. The interest of revisiting the self-pressurization concept comes from the belief that it can simplify the pressurization mechanism and produce lighter systems.

There are currently five main organizations leading the space exploration [1]: NASA from the United States of America, ROSCOSMOS from Russia, ESA from Europe, JAXA from Japan and CNSA from China. The number of launchers in use is very high. Through the most successful launchers of the present-days it is possible to understand the technology in use. For example, one of the most recent engines is the Merlin, the upper stage engine from Falcon 9. This engine has as its propellants liquid oxygen and Kerosene. One of its characteristics is that it allows operation with different OF ratios due to the flow trimming. Similar to what is proposed in this project, its cooling is done by regenerative cooling. The engine characteristics give the five main parameters to define in this work: propellants in use, properties of the burn (OF, flame temperature, specific impulse, etc.), sizing, material and heat transfer analysis.

As one of the objectives of this study is to evaluate the feasibility of building a self-pressurized system, all the design should take it into account. The concept of self-pressurization through regenerative cooling relies on the pressurization of the tank using heat from the combustion chamber. Which means that the cooling, in this case, would not only serve to keep the system integrity, but also keep the pressure in the fuel tank. The system stability should be assured by its capacity to correct deviations. Figure [1] shows that for
a range of OF between 0.5 and 1.5 (which is the ideal range of operation), the decrease of
this ratio should trigger the same change in temperature.

Therefore, if the pressure in the fuel tank decreases, the OF will increase, which leads
to a higher flame temperature, that increases heat transfer and, therefore, the pressure in the
tank.

II. BACKGROUND

There are three types of rockets motors: solid, liquid and hybrid. Their designations are
based in the physical state of the propellants involved. There are also mono-propellants and
bi-propellants engines. The first ones are made of a single substance and their use relies on
their exothermal decomposition by a catalyst - for example, hydrogen peroxide or hydrazine.
In the second case, there are two reactants that are stored apart. In this particular project we
are dealing with a bi-propellant liquid rocket engine. The liquid propellant engines are usu-
ally more efficient in terms of specific impulse - Isp, can be shut down and may be throttleable
and re-startable if necessary [2]. The system of a liquid engine can be divided into six main
parts: thrust chamber - which contains the nozzle, injector and the combustion chamber;
tanks - for the reactants; feed mechanism - either using pumps or pressurant gases - in some
cases both mechanisms are combined; power source to electrical modules; piping; control
systems. The combustion chamber is the main

\[
\frac{A_e}{A_t} = \frac{1}{Ma_e} \left( 1 + \frac{2(\gamma - 1)}{\gamma + 1} Ma_e^2 \right)^{\frac{\gamma + 1}{2(\gamma - 1)}}
\]  

(1)

Where \( Ma_e \) corresponds to the Mach number at the exit and \( \gamma \) is the heat capacity ratio. The
throat area is computed using the sonic throat assumption. The following equation can be
manipulated in order to solve it for the maximum accepted area to have sonic conditions,
given by \( A^* \), from the drag coefficient - \( C_d \) - \( \gamma \), mass flow rate - \( \dot{m} \) - \( \rho_l \) and pressure - \( P_l \).

\[
\dot{m} = C_d A^* \sqrt{\frac{2 \rho_l}{\gamma + 1}} \left( \frac{2}{\gamma + 1} \right)^{\frac{\gamma + 1}{2}}
\]  

(2)

The material should also be carefully analysed. Some materials are not compatible with some
propellants, for example, ammonia deteriorates
copper. It is also desirable to have a material with strong mechanical properties to ensure that the chamber is capable of withstanding both pressure and temperature conditions. The temperatures in the chamber during the combustion are higher than the service temperature of most of the materials, whereby the need for chamber cooling must be considered during the design to avoid damage. This is determinant for calculating wall thickness and the choice of the material.

The heat transfer is a crucial part of the design. Chamber heat is mostly transferred by convection from the hot gases to the wall, and then conducted through the wall. There is a significant increase of the heat transfer in the throat, which means that the cooling must be exceptionally effective in this area to avoid significant damage. Cooling can be done mainly by a combination of five different methods:

- **Regenerative cooling** - It is the most used method. One or both propellants pass through conduits in the chamber’s outer wall in order to cool it, before being injected.
- **Film cooling** - In this case, as its name indicates, the wall surface is protected from excessive heat by a thin film of a coolant or propellant, that is introduced in the chamber around the injector or through orifices in the chamber wall. It can be used in combination with regenerative cooling.
- **Transpiration cooling** - It is similar to film cooling. In this case the walls in the chamber are porous. A coolant is introduced through them at a rate that allow the desired temperature to be maintained.
- **Ablative cooling** - This method was mainly used in solid motors, although it is also suitable to liquid engines of short duration and low chamber pressure. For this method the wall material is a thermal insulator, resulting in a poor heat transmission to the outside. In the inner chamber wall the material suffers melting, vaporization, and chemical changes to dissipate heat.
- **Radiation cooling** - The heat is radiated from the surface to the outer wall of the chamber. This type of cooling is preferable in regions with low heat flux as, for example, nozzle extensions.

The most relevant performance parameter is the specific impulse - $I_{sp}$ - which SI unit is $\frac{Ns}{kg}$. It depends on a wide range of factors such as chamber pressure and propellants ratio. It is given by the ratio between the engine’s thrust - $F$ - and the total mass flow rate - $\dot{m}$, which is defined by \[ (3) \]

$$I_{sp} = \frac{F}{\dot{m}}$$

This parameter depends on the burn and expansion efficiency. It varies with $OF^{\frac{1}{2}}$, as having a lean or rich mixture is determinant to the combustion efficiency. This ratio can be calculated from the stoichiometric combination of the fuel and the oxidizer.

To predict the engine performance and the combustion characteristics software is available from NASA - CEA \[ 4 \] \[ 6 \] - that is capable to compute these parameters. This software, called Chemical Equilibrium with Applications, was developed to calculate chemical equilibrium and properties of complex mixtures. It has specific functionalities for rocket problems, and was used during this project.

The injector is the component responsible by introducing the reactants into the combustion chamber. Usually the propellants are in liquid state when injected. Therefore the injector must be capable of breaking down the stream into small droplets and maximize the mixing in order to achieve an effective burn. There is a drop of pressure in the injector that must be considered when designing the system. It can be estimated by the non saturated throat equation, that comes from the mass conservation equation.

\[ (4) \]

$$\dot{m} = C_d A_{inf} \sqrt{2p \left( \frac{\gamma}{\gamma - 1} \right) \left( \left( \frac{P_c}{P} \right)^{\frac{\gamma}{2}} - \left( \frac{P_c}{P} \right)^{\frac{\gamma+1}{2}} \right)}$$

There is a lot of research about injectors and their influence in the engine behaviour, regarding the orifice pattern, angles on injection, etc. Although it is a field with a considerable complexity, the goal of this project was to design a \[ 1 \] Ratio between oxidizer an fuel.
simple injector. Having a good mixture is the key to achieve an efficiency near the expected.

III. Mathematical model

The mathematical model in this project serves to determine if the auto pressurization concept is stable. The model in use is iterative. The objective is to determine the pressure evolution in the tank when the heat transfer is responsible for increasing the remaining fuel’s pressure. The layout considered is in figure 2.

\[ \frac{dm}{dt} = -m_F \Rightarrow m = m_0 - \int_0^t m_F \, dt \]  \hspace{1cm} (5)

In order to calculate the fuel’s mass flow rate - equation 6 - it is necessary to know the velocity, which can be calculated with equation 7, which is a manipulated form of the Bernoulli equation. Notice that, in this equation, \( k \) represents the pressure losses in each section of the piping lines. In the mentioned equation the term \( f \) represents the Darcy friction factor in the system. Both the presented terms can be estimated using available reference and [7].

\[ \dot{m}_F = \frac{AV}{\nu_g} \]  \hspace{1cm} (6)

Where \( A \) is the area of the piping, \( V \) is the velocity and \( \nu_g \) is the specific volume.

From the Bernoulli equation in [7] it is possible to estimate the velocity, in [8]

\[ V = \sqrt{\frac{2\nu_g (P - P_0)}{\Sigma k + fL}} \]  \hspace{1cm} (8)

Applying an energy balance in the tank we have equation 9 where \( u \) and \( m \) are defined by equations 10 and 11 respectively.

\[ \dot{Q} = \frac{d}{dt}(mu) + m_F h_g \]  \hspace{1cm} (9)

\[ u = u_l + x(u_g - u_l) \]  \hspace{1cm} (10)

\[ m = \frac{Vol}{V} = \frac{Vol}{v_l + x(v_g - v_l)} \]  \hspace{1cm} (11)

The \( x \) value is the gas fraction, that can be estimated through equation 14. The heat rate is given by equation 12. As it is an iterative model, it is possible to compute the evolution of the properties in each step, as for example the temperature of the fluid in the tank.

\[ \dot{Q} = AU\Delta T \]  \hspace{1cm} (12)

The variable \( A \) is the area, \( \Delta T \) is the temperature difference and the \( U \) is explained in equation 13.

\[ U = \frac{1}{\frac{1}{h_ch_c} + \frac{1}{h_vch_v} \ln \left( \frac{v_g}{v_l} \right) + \frac{1}{h_{ch}h_{cv}}} \]  \hspace{1cm} (13)

Where \( h \) are the convection coefficients for the convection in the chamber and at the vaporizer.

\[ x(t) = \frac{m_g}{m} = \frac{\int_0^t \dot{Q}/h_f \, dt}{m_0 - \int_0^t m_f \, dt} \]  \hspace{1cm} (14)

To close the problem it is necessary to include an extra equation. When using the sonic throat assumption it is possible to write the equation in order to the pressure value, so it can be estimated.

\[ n_l = n_F + n_{ax} = \frac{0.6847 \rho_0 A^*}{(RT_0)^{1/2}} \]  \hspace{1cm} (15)

When applying equation 15 it is considered that the throat is sonic, which is true as long as the chamber pressure is about twice as the atmospheric pressure [7].
Method

Given the initial pressure of the tank - set as 20 bar - the burning process starts. The flame temperature depends on the oxidizer fuel ratio. The polynomial that describes the relation is obtained using CEA software, by varying the OF value and registering the given flame temperature. This temperature is crucial to estimate the heat transfer, as it will depend on it. The heat is absorbed by the fuel in the vaporizer, and its properties will change. Through the energy balance it is possible to determine the new pressure value. This new state, with the updated properties, will result in a different fuel mass flow and, therefore, in a different OF, which will lead to new temperatures in the chamber and therefore, new values of heat rate. This creates a cycle during the burn, where the new properties in the tank are calculated at each step.

It is important to refer that this is a simplified mathematical model that does not contemplate some losses during the process. Some of the consulted literature [8], [9] and [10] provide a mathematical model to incorporate these losses by friction and heat transfer. However, it was decided to make a simpler model relying on the assumption that the system is isentropic with heat transfer. In fact, the second principle of thermodynamics (equation 16), does not discard this possibility for \( \frac{dQ}{T} < 0 \), since \( d\sigma > 0 \).

\[
\frac{dQ}{T} + d\sigma = dS \tag{16}
\]

The thermodynamic properties of the saturated fluid were found on NIST [2]. The polynomials that correlate pressure with internal energy, enthalpy, etc. were computed from the mentioned saturated property tables, using Matlab.

IV. EXPERIMENTAL WORK

The departure characteristics for this engine are in table 1.

<table>
<thead>
<tr>
<th>Pressure</th>
<th>Oxidizer</th>
<th>Fuel</th>
<th>Thrust</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 bar</td>
<td>Gaseous Oxygen</td>
<td>To Define</td>
<td>25 N</td>
</tr>
</tbody>
</table>

As it was previously mentioned, the layout should be flexible enough to enable the operation with external and auto pressurization. Figure 3 shows the layout used. The dotted line between the vaporizer and the tank can be opened to allow gases from the vaporizer to pressurize the tank. When this line is closed a nitrogen bottle, connected to the fuel's tank is responsible for the pressurization.

Manufacturing the small liquid rocket engine a significant part of the work has to do with sizing. It was an iterative process due to the different options in each step. Nevertheless, as found on literature [3], a sequence of computation was followed: propellant choice, OF calculation, total flow rate computation, nozzle sizing, combustion chamber, chamber wall thickness and cooling.
The fuel must fulfill the requirements of this project, there were several parameters analyzed: critical pressure and temperature, enthalpy of vaporization and specific impulse when combined with oxygen. From the three candidates - Ammonia, Ethanol and Propane - Ammonia was chosen. It has good cooling capabilities and can achieve high pressures with relatively low temperatures. Part of these estimations were done using CEA software and the other information was obtained from NIST.

The heat transfer analysis shows that it is possible to have a proper cooling with the engine characteristics.

The injector used, in figure 4, has swirl to cause a recirculation bubble which will anchor the flame and prevent undesired instabilities.

![Figure 4: Swirl injector.](image)

The final design can be consulted in table 2.

<table>
<thead>
<tr>
<th>Item</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>ENGINE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OF</td>
<td></td>
<td>1.4</td>
</tr>
<tr>
<td>Total mass flow</td>
<td>kg/s</td>
<td>0.00999</td>
</tr>
<tr>
<td>$I_F$</td>
<td>m/s</td>
<td>2501.6</td>
</tr>
<tr>
<td>Power</td>
<td>kW</td>
<td>31.3</td>
</tr>
<tr>
<td>Chamber diameter</td>
<td>mm</td>
<td>30</td>
</tr>
<tr>
<td>Throat diameter</td>
<td>mm</td>
<td>3</td>
</tr>
<tr>
<td>Area ratio</td>
<td></td>
<td>3.2</td>
</tr>
<tr>
<td>Chamber pressure</td>
<td>bar</td>
<td>15</td>
</tr>
<tr>
<td>Chamber material</td>
<td></td>
<td>Stainless Steel 304</td>
</tr>
<tr>
<td>Burn time</td>
<td>s</td>
<td></td>
</tr>
</tbody>
</table>

| OXIDIZER | Oxygen Pressure | bar  | 40 |
|          | Temperature     | K    | 293 |

| FUEL      | Ammonia Pressure | bar  | 40 |
|          | Temperature      | K    | ~300 |

V. Tests

Figure 5 shows the test stand that was used during the test campaign. In order to get use to the operation of the test stand, the first tests were performed with ethanol, which is safer and easier to handle than ammonia.

![Figure 5: Test stand used.](image)

The instrumentation in the test stand allow to measure the pressure, temperature and the thrust. The first tests were external pressurized.

![Figure 6: Temperature evolution during the test.](image)

From the temperature plot, in figure 6, it is possible to understand that the flame was closer to the thermocouple than in previous tests, once the chamber’s temperature reached almost 400 deg C. The temperature in the vaporizer, even in this test, where it was already above the ambient temperature, did not reach the high temperatures that were observed in the ethanol case. This allowed to operate the
test stand for longer tests, what was not possible with ethanol.

In the pressure chart, in figure 7, the two lines are very different from the previous test. There is a hard start at the beginning of the burn. The chamber pressure starts to decay around 7 seconds after the beginning. This happens because the ammonia ends. As it was explained before, this test was performed after an self-pressurized test, which means that part of the ammonia available was spent in that test. The vaporizer’s pressure, represented by the blue line, has three different stages.

The thrust, which can be seen in figure 8, achieved during the test was satisfactory, around 23N - for a projected value of 25N. It starts to drop when the fuel tank runs out of ammonia. It is possible that the stoichiometry was not the desired, specially when ammonia starts to evaporate. Although, with the lack of instrumentation to actively control the fuel mass flow rate, the results are satisfying.

The plume obtained during the test can be seen in figure 9.

For the self-pressurized test two types of test were made: low OF and high OF. It was decided to predict the engine’s behaviour when operating in different regions on the curves showed in figure 1.

The first test was made with higher OF. From the pressure plot it is possible to understand that the vaporizer line has the same tendency predicted from the mathematical model. The first depression in the vaporizer pressure line is the point where nitrogen in the fuel’s line stops being responsible for the pressurization. It is possible to see a small decrease in the vaporizer’s pressure, followed by its increasing due to the regenerative cooling, from where it behaves as it was predicted. Although, in the case of the chamber pressure, the pressure starts to increase, as was expected, and then it decays. There is a small increase of the pressure and its decay, until the valves are closed around 14 seconds.

During the test the sound denoted the that the engine’s behaviour was fickle, what can be translated by the chamber’s pressure plot, where it is possible to understand that the pressure was constantly trying to rise, but it decayed few moments after, ending by decaying consistently until the valves were closed. The behaviour of the pressure in the vaporizer is close to the predicted by the mathematical model for this case.

In the second case, with low OF, the oxygen
Figure 10: Pressure evolution during the test.

bottle was regulated to 20bar and the fuel’s line was initially pressurized with 18bar. The flow control valves were also adjusted with the same height. The pressure in the chamber resembles more to a step than in the previous case. The pressure in the vaporizer shows an increase, although it is notorious that there are some oscillations in the pressure growing. Figure 11 shows the pressure evolution during the test.

Figure 11: Pressure evolution during the test.

The discrepancy between experimental and theoretical results has to do with the settled pressure in test stand, which was lower than the theoretical. However, the tendency is similar.

VI. CONCLUSIONS

This master thesis marks the beginning of a company’s project to build a successful engine. It was a work based on research and development that, as it was expected, had successful and unsuccessful points. After all it was important to understand the system behaviour.

In this project it was possible to accomplish the objectives that were proposed at the beginning. To simplify, it is possible to divide the project in two main parts: work with external pressurization and with self-pressurization.

The external pressurized system was stable and behaved as expected. It was possible to build a simple and low cost engine, properly sized and in which the heat transfer was well estimated. The heat transfer analysis was an important point of the work, which assured material safety and, therefore, the success of the test campaign. The data collected leads to the conclusion that, with ammonia, the objective of having gaseous injection was achieved.

The second part of the work, that had to do with the study of the self-pressurized system, allowed to prove that the concept is feasible and it is worth studying and investing in. The results obtained with this type of pressurization were different from those previously obtained, which were closer to the predictions. However, the fact that there is an explanation to this discrepancies proves that there is more to study about the concept. The fact that the system was able to sustain an effective burn during a brief time was a success.

In the beginning of this document there is an explanation about how the system would be able to correct itself through the change of the flame temperature with the OF. Experience and the model showed that there are actually differences when operating with low and high OF.

i. Future Work

The company intends to increase the engine’s capacity. Therefore, using the same method as before, the chamber was resized in order to achieve a thrust of 300N, using the same test stand. The objective is to change the minimum possible.

To increase thrust is necessary to increase
pressure, in order to achieve reasonable dimensions and a sonic throat. The security valves installed can go up to 70bar, so the chamber’s pressure is fixed at 50bar.

It would be important if a flow meter was installed in the test stand, allowing the operators to know the actual fuel flow rate and, therefore, the OF.

The flame’s temperature is also unknown. The thermocouple that was meant to be used to measure the temperature in the plume was damaged. Acquiring a new one should also be considered.

VII. Acknowledgments

I would like to thank Omnidea Lda. for offering me this fellowship to develop my master thesis. All the experimental work was developed in Omnidea facilities and the company supported all the costs involved. A special word for Horácio Moreira, my supervisor at the company. Thank you for the patience and for teaching me so much. A heartfelt thanks to Tiago Pardal, the owner of Omnidea Lda and the inventor of this concept, for giving me this opportunity.

References