Regression rate study in a small Hybrid Rocket Engine using N_2O/paraffin propellant

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Abstract: **In the frame of the FAST20XX project under the supervision of ESA, two hybrid rocket engines are developed at Université Libre de Bruxelles (ULB) in collaboration with the Royal Military Academy of Belgium to assess the performance of paraffin/N_2O propellants. The goal behind the study is to measure the regression rate and optimize the size of ALPHA, which is a sub-orbital vehicle designed for space tourism.**

Keywords: **hybrid rocket, ALPHA, nitrous oxide, paraffin**

NOMENCLATURE

$\dot{r}$: $regression\ rate$

G_{ox}: $oxidizer\ flux\ (\frac{kg}{m^2.s})$

a, n: coefficients depending on the chosen propellant couple

I. INTRODUCTION

In the frame of the FAST20XX project, experimental work is done at ULB to measure the N_2O/Paraffin performance using a lab-scale hybrid rocket motor and its impact on the ALPHA vehicle. The ALPHA vehicle incorporates technology for low energy suborbital transportation, which necessitates the use of a launch aircraft to launch the ALPHA for short sub-orbital flights. The ALPHA vehicle is configured to carry four adult passengers including the pilot to a minimum altitude of 100km. After separation from the launch aircraft the vehicle ignites its inboard rocket propulsion system. Conventional liquid and solid propellants do not seem suitable for ALPHA due to financial, safety and ecological constraints. Instead a low cost, environmentally friendly and non-toxic hybrid propulsion system is chosen. The hybrid propulsion system is based on liquid nitrous oxide in combination with a solid polymer fuel selected as a baseline for ALPHA. For further reading an overview of the sub-orbital concept ALPHA can be found in Adirim et al. [1].

The purpose is to retrieve the "a" and "n" coefficients of the classical regression law (Eq. 1) and compare the performance with the HTPB/N_2O hybrid engine.

$$\dot{r} = a * G_{ox}^{n} \quad (1)$$

II. EXPERIMENTAL WORK

A. Test bench

Since the end of 2006, ULB is developing with the Royal Military Academy of Belgium a test bench to study the Paraffin/N_2O regression rate. Throughout the tests, 3 engines were constructed with some improvements at each step to ensure proper data acquisition and safe firing.

The purpose is to obtain a representative 1kN thrust engine.

The test bench is composed of four parts: the injection line, the ignition part, the combustion chamber, the nozzle and the venting.

The injection line (Fig. 1) is composed of three N2O bottles in parallel. Each one is equipped with a 1/4" hose and a solenoid valve to control independently each one. The three bottles merge on a 1/2" hose, which is connected to the engine through an injector.

Figure 1: Injection line

For the tests, two types of injectors (Fig. 2) were used: a hollow cone and a full cone pattern injector. The first one has an angle spray of 50° and the second one of 60°.

Figure 2: Full cone (left) and hollow cone (right) injectors

A pyrotechnic cartridge made in collaboration with the Royal Military Academy commands the ignition.
It is composed of four elements (from left to right in Fig. 3):
- a professional igniter
- spherical powder
- ignition powder
- extruded grain made from AP/Kraton/Aluminum.

The mixed grain is extruded and after several tests, we obtain the following dimensions:
- 45 mm length
- 21.5 mm outside diameter
- 8 mm inside diameter

Prior to any combustion test, the effect of the pyrotechnic cartridge only on the paraffin grain is observed. The results demonstrate that the paraffin grain loses a few grams of material and is not affected by this one. Thus the influence must not be taken into account when the regression rate is calculated.
The temperature attained a value exceeding 1200°C which is highly above the N_2O dissociation temperature and ensure the start of the combustion.

Figure 3: Pyrotechnic components

The engine is made of steel and is composed of three parts:
- the precombustion chamber
- the combustion chamber & the afterburner
- the nozzle.

The precombustion chamber (Fig. 4) permits the N_2O vaporization and dissociation before reacting with the melting paraffin inside the combustion chamber. It is equipped with three type K thermocouple equally distributed along the circumference and a housing for the ignition cartridge. The central port is the injection line entry.

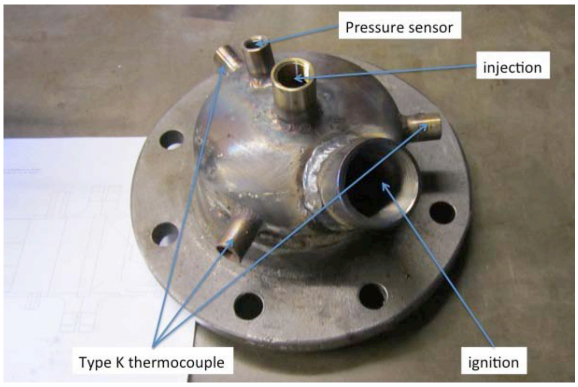

Figure 4: Precombustion chamber

The combustion chamber (Fig. 5) is the central part of the engine. It is longer than the grain and the empty space serves as an afterburner to let the propellant reacting and have a better combustion efficiency. In order to avoid the paraffin grain embedding into the injector and a reaction in the outer face, a ring is placed between the precombustion and the combustion chamber. Two sensors capture the pressure and the temperature using a type C thermocouple.

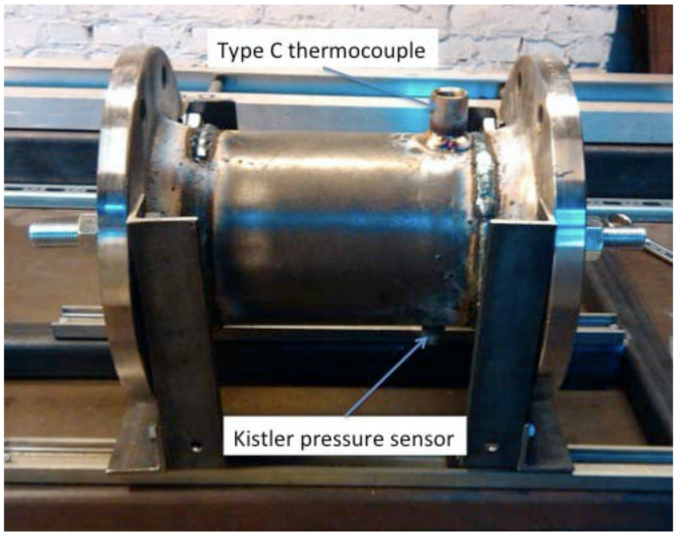

Figure 5: HRE combustion chamber

The nozzle (Fig. 6 right) closes the engine. It is made of graphite, which resists better to abrasion and is fitted in a piece (Fig. 6 left) that gives a smooth transition to the gases before entering the nozzle.

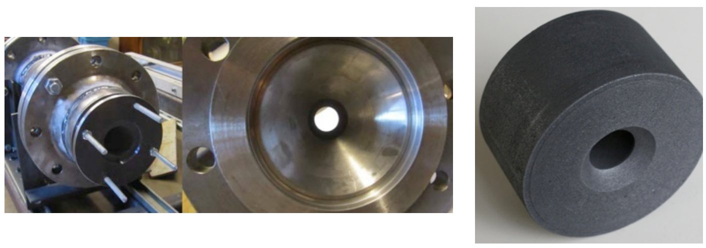

Figure 6: Graphite nozzle and its support

To prevent the hot exhaust gas from entering the line after the combustion test and avoid a N_2O dissociation reaction [2], it was decided to add a venting line using N_2 at 10 bars to eject the residual gazes inside the combustion chamber and prevent any explosion hazard.

B.Experiments

1)Injection tests

Prior to any combustion, multiples cold tests were done in order to characterize the injection line. Our goal is to reach a 1 kN thrust engine.

Difficulties encountered in the nitrous oxide (N_2O) injection system development were confirmed by several sources citing this part of a nitrous oxide fed hybrid rocket as a neuralgic point. Nitrous oxide's advantage of being self-pressurized at ambient temperature brings with it the problem of its very high sensitivity to oxidizer feed line pressure losses causing rapid vaporization and hence a largely reduced available mass flow rate at the entrance of the combustor. In order to size our test bench correctly for future tests, an analysis of the phenomenon and of solutions available to cope with this pressure loss problem has been undertaken.

The first idea was to use a manual gate valve to control the flow and the thrust by the way. The first test gives the results shown in Fig. 7.

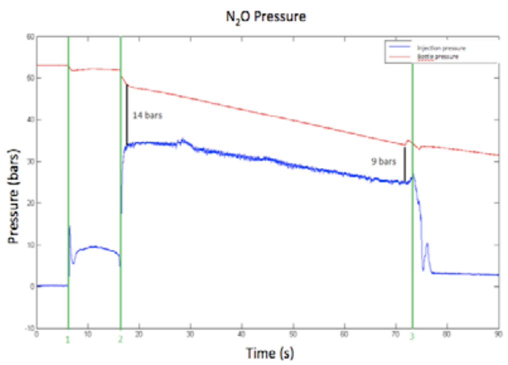

Figure 7: Pressure evolution during the 1st injection test

We observe high head losses in the line. The P-T diagram (Fig. 8) clearly indicates that the vapor phase is dominant in the flow.

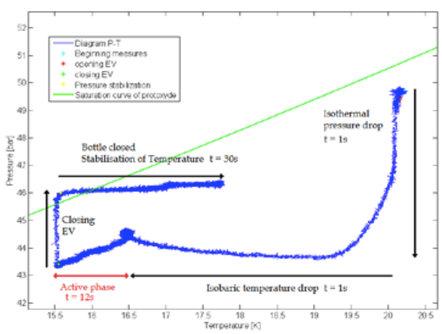

Figure 8: P-T diagram during the 1st injection test

The second phase of the study consists of the head losses measurement of each injection line component. We found from the study that the manual gate valve is responsible of a 10 bars pressure drop. So it was decided to remove it.

Fig. 9 gives the flow in a P-T diagram without manual gate valve.

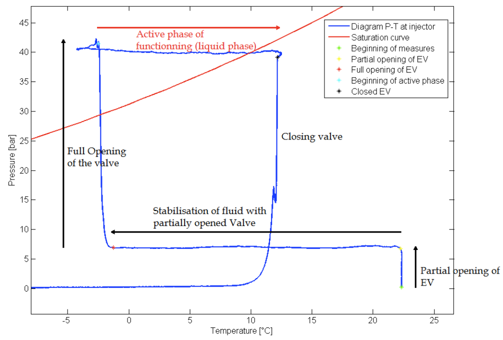

Figure 9: P-T diagram for the 2nd test

The curve shifts upwards, above the saturation line, indicating a liquid phase in the injector. This ensures proper atomization of the N_2O and a better combustion inside the chamber.

Despite the increase of performance, the flow is too low to reach a 1 kN thrust. As gas companies deliver the bottles, they are studied for medical application and the exit orifice induce important head losses. The goal is to vaporize the N_2O to put to sleep the patient.

To increase it, three solutions were envisaged:

- the use of the NOS system for competition cars with a pressurization system,
- the construction of an intermediate tank,
- the use of multiple bottles in parallel.

The first solution is elegant as the system comprises a pressurization system but once the bottles are empty, it is not possible to fill them by gas suppliers. Moreover, the flow is too low for our application.

The second solution is difficult because the tank must be tested until burst and it raises security problems.

So the easier and safest way is to put multiple bottles in parallel. Even with 3 bottles, the flow is lower than expected. So the only solution will be to construct an intermediate tank with a larger exit orifice and a pipe with 2 entries: one for a pressurization and one as exit. It will solve the vaporization problem and ensure a fluid phase all along the line.

2)Hot tests

17 tests were made in order to characterize the regression rate. All of them are launched by a LabView interface that controls the timing.

The sequence starts with the ignition, followed by the injection. After a pre-defined combustion duration, the oxidant flow is stopped and N_2 is injected in the engine for venting to prevent any explosion hazard. The remaining paraffin is weighted to know how much fuel has reacted.

The time-averaged regression rate is given on Fig. 10. As we can observe, the mean regression rate is around 4 to 5 mm/s. As read in existing literature, it is higher than for HTPB/N_2O (1 mm/s) [3] as expected but more surprisingly, the value is also higher than the values found in literature for the same fuel/oxidant (3 mm/s) [4]. In fact, we found results equivalent to the SP-1a paraffin/GOX used by the University of Stanford [5].

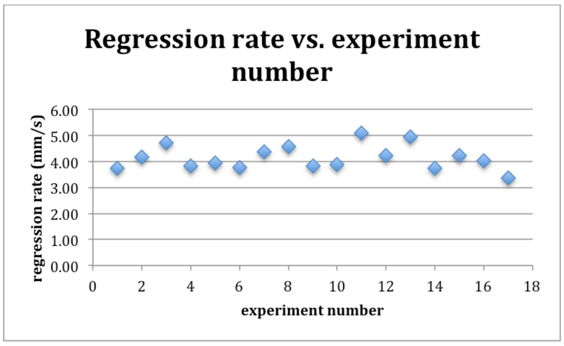

Figure 10: Regression rate

In Fig. 11, we have the mean O/F ratio given for each experiment. We observe that the values are below the design value of 6.7, which gives the best theoretical I_{sp}.

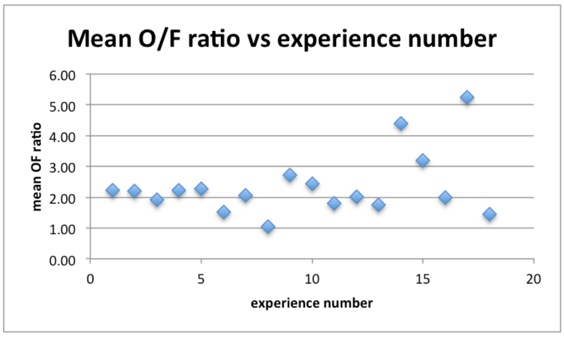

Figure 11: Mean O/F ratio

This is coherent with the tests video where a lot of smoke is observed in the exhaust flame, indicating that the paraffin has not fully reacted during combustion. This fact explains why the calculated I_{sp} (Fig. 12) is far below the theoretical values.

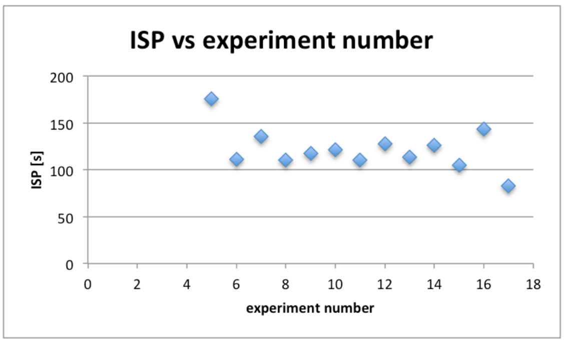

Figure 12: Obtained ISP

The results can be explained due to a bad vaporization of the N_2O flow that ejects the paraffin without reacting or by an incomplete combustion due to a too short stay in the afterburner.

III. Conclusions and Perspectives

The hot tests give encouraging results and the N_2O/paraffin couple gives higher regression rate than N_2O/HTPB. That implies than the N_2O/paraffin engine could be more compact.

The injection line can be improved by the construction of a pressurized tank that permits to increase the flow and have a fluid phase in the injectors.

The ignition cartridge is very reliable, as we do not notice any malfunction during all the tests.

In order to retrieve the ‘a’ and ‘n’ coefficient of the regression law, a device is developed to measure in real time the thickness of the paraffin grain. It is composed of a printed circuit board with electrical resistances in parallel and molded in the grain. When the grain is burning, the resistances are destroyed and we can observe a voltage step in the LabView interface. The circuits are given in Fig. 13.

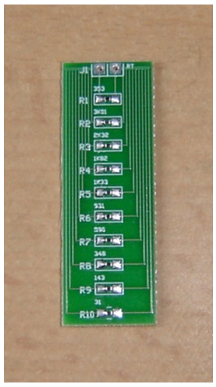

Figure 13: Regression rate sensor

Once the sensor is ready to be used, further work is planned with some additives in the paraffin grain such as metallized particles to study the effect on the regression rate.

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