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# Characterization of Magnesium Diboride as an Additive for Paraffin-Based Fuel Hybrid Rockets

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## Abstract
Previous studies carried out by the Aero-Thermo-Mechanics Department at Université Libre de Bruxelles and the Belgium Royal Military academy indicate that Magnesium diboride, $MgB_2$, is a candidate for paraffin-based fuels performance enhancement agent. The main advantage of using Magnesium diboride lies in the fact that this additive is more stable and easier to handle than other metal hydrides, such as Lithium Aluminium Hydride and $MgH_2$. This study presents the results of a series of experimental investigations using the MOUETTE slab burner and the 1kN hybrid rocket motor to characterize the paraffin-fuel samples dopped with $MgB_2$.

## 1. Introduction

Hybrid Rocket Engines (HREs) could replace existing bipropellant liquid engines for some specific applications such as small launchers, the upper stage of launcher vehicles, and decelerator engine for re-entry capsules. On the other hand, hybrid rocket technology has some development challenges in comparison with more mature chemical propulsion systems and one of the main drawbacks of hybrid technology is the low regression rate of the solid fuel, hence relatively poor combustion efficiency and combustion instability [1 - 2].

In order to overcome the low regression rate, nowadays various HREs use paraffin as the main component of the fuel grain [3], because of the low cost and high regression rate advantages. However, pure paraffin has poor structural characteristics and sometimes low combustion performance due to the fuel's internal ballistics behaviour.

In HREs, the fact that the fuel is in the solid phase makes it very easy to add solid performance-enhancing materials such as Magnesium diboride ($MgB_2$). This enables the hybrid rockets to gain a specific impulse ($I_{sp}$) and density advantage over a comparable hydrocarbon-fuel liquid system. Additionally, metal additives can be used to reduce the oxidizer-to-fuel (O/F) ratio for maximum specific impulse, thereby enabling a reduction in the required mass of liquid oxidizer [4]. Theoretically, any additive used in solid motors can be applied in hybrid.

The most common materials used as hybrid rocket fuels are paraffin, hydroxyl-terminated polybutadiene (HTPB), polymethyl-methacrylate (PMMA), and high-density polyethylene (HDPE). Some small-scale, low thrust experimental hybrid rocket also applies (not usually) polylactic acid (PLA), acrylonitrile-butadiene-styrene (ABS), polyethylene-terephthalate-glycol modified (PET-G), and, in the past, some exotic elements as graphite, gel-gasoline and even wood [5].

The most frequent fuels used in hybrid rocket applications are HTPB and HDPE for long burning times and paraffin for high performance. The *SpaceShipTwo* (Virgin Galactic), a reusable spacecraft designed to carry eight persons into space (~100 km), is powered by a hybrid rocket motor using HTPB as fuel. In the past, a United States company, AMROC (American Rocket Company) developed and tested large-scale hybrid motors (ranging from 5.5 kN to 1.1 MN) using liquid oxygen and HTPB as propellant [6]. Thus, the manufacturing of hybrid rocket fuels covers various thrust levels and applications.

The development of fuels for hybrid rockets is safe because most blends are chemically inactive in atmospheric conditions. Usually, the most common technique to produce hybrid rocket fuel grains is to melt the material and shaped it in a specific form (cylindrical, double-D, 7-cylinder cluster, wagon wheel, 4-port wagon wheel, etc.) [5]. Sometimes,

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machines are used in this process to spin the fuel grain when it is solidifying or controlling the temperature to try to avoid imperfections.

This research combines some of these techniques to produce paraffin-based grains doped with metal powder. A series of 2-D small-scale tests were carried out with the ULB/ATM MOUETTE (*Moteur OptiqUe pour ÉTudier et Tester Ergols hybrides*) slab burn using two different concentrations of Magnesium diboride, 5%, and 10%, respectively. After, two samples doped with 5% $MgB_2$ were tested at the 1 kN ULB hybrid rocket motor (ULB-HRM) to develop techniques for mixing paraffin and this additive in higher scale quantities. The main advantage of the Magnesium diboride in comparison with Boron powder is that, unlike Boron, $MgB_2$ burns completely when ignited with oxidizers.

## 1.1 Preliminary studies using Magnesium Diboride as HREs fuel additive

Previous studies carried out by the Aero-Thermo-Mechanics Laboratory (ATM) at Université Libre de Bruxelles (ULB) and Belgium Royal Military academy (RMA) indicate that, in some conditions, Magnesium diboride, $MgB_2$, is a candidate for paraffin-based fuels performance enhancement. Magnesium diboride is a black powder with a molecular weight of 45.93 g/mol, commercially produced with 100 mesh and ≥ 99% trace meta basis (CAS number 12007-25-9).

The main advantage of using the Magnesium diboride lies in the fact that this additive is much more stable and easier to handle than other metal hydrides, such as LAH (Lithium Aluminium Hydride) and $MgH_2$ (Magnesium hydride). The tests using the 2-D RMA Hybrid Rocket, Figure1, were done at low oxidizer (nitrous oxide) mass flow rate and chamber pressure, from 1.1 to 5.5 bar [7], and burning times from 1.1 to 5.5 seconds. In the ULB/ATM and RMA previous works [7], paraffin fuel doped with Magnesium boride was produced by melting paraffin and mixing the $MgB_2$ powder using a commercial solvent, in a very slow process of solidifying at a controlled temperature, Figure 2.

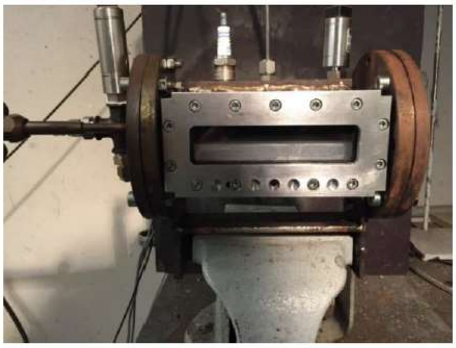

Figure 1: RMA 2-D burner [7]

The density of the fuel matrix, Table 2, was determined in comparison with the same sample produced with commercial pure paraffin, 887.5 kg/m$^3$. This parameter is closely related to the mass budget of a propulsive system. In parallel, hardness tests showed that $MgB_2$ doesn't bring any benefit, however some more precise measurements must be done to fully characterize this parameter.

Figure 2: Paraffin dopped with $MgB_2$ [7]

These preliminary tests indicate that the regression rate of paraffin dopped with 5% and 10% of $MgB_2$ is slightly higher than the one with pure paraffin for low combustion chamber pressure (~1.1 bar). Even with a regression rate near the

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average value of the pure paraffin, the advantage of doping it with Magnesium boride comes also in terms of fuel density, which allows the decreasing of the combustion chamber dimensions.

Table 1: Density of Paraffin sample doped with Magnesium boride, $MgB_2$

| **Percentage of $MgB_2$ (in weight)** | **Density of the grain ($kg/m^3$)** | **Relative increase of the density** |
|---|---|---|
| 2.5 % | 902.6 | ~ 1.7 % |
| 5.0% | 918.4 | ~ 2.7 % |
| 10.0% | 948.3 | ~ 6.4 % |
| 15.0 % | 976.8 | ~ 9.1 % |

## 2. Experimental setup

In this study a series of experimental investigations were carried out using the MOUETTE (*Moteur OptiqUe pour ÉTudier et Tester Ergols hybrides)* slab burner, Figure 3, and the 1kN ULB hybrid rocket engine, Figure 4. The MOUETTE slab-burner helps to characterize the samples from the atmospheric pressure to up to 10 bar, and a quartz glass window allows measurements with visualization techniques, such as Schlieren techniques. General information about the ULB/ATM MOUETTE slab-burner is presented in [8].

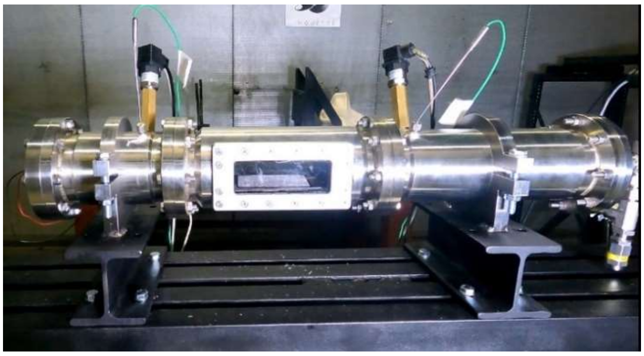

Figure 3: MOUETTE slab-burner with a paraffin grain doped with 5% $MgB_2$

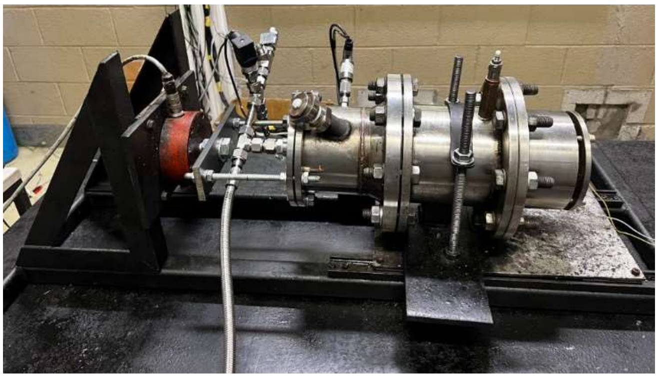

Figure 4: Trim pad at the 1-Wing Belgium Air Base, with the ULB-HRM

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The ULB 1kN motor (ULB-HRM) has a modular concept, containing three main parts (pre-chamber, combustion chamber, and post-combustion chamber with convergent-divergent nozzle). The pre-chamber is 100 mm long, a combustion chamber accommodates Ø140 mm outer diameter fuel grain and a 45 mm length of post-chamber. The convergent-divergent nozzle has a graphite shell that covers the critical section and the divergent part. The throat section is Ø22 mm in diameter. The total motor length is 440 mm, and the external diameter of the combustion chamber is Ø154 mm. More information about the ULB 1kN engine is found in [9].

## 3. Grain manufacturing

The first technique to mix paraffin and $MgB_2$ was developed in [7], but some improvements were done. A defined quantity of paraffin is melted at a controlled temperature, between 70ºC and 100ºC. After the complete melting of the paraffin, the defined percentage of Magnesium diboride is added, and a 30 minutes mixing process starts. Figure 5 shows the apparatus and the fuel grain mould. A trying to manufacture the grain without a commercial solvent to help the mixing was done, however, a major part of the metal powder was deposited in the base of the mould, resulting in an irregular vertical distribution, not observed when the solvent is used. The amount of commercial solvent is less than 0.5 % of the total net dry weight of the additive.

Figure 5: MOUETTE fuel grain during the manufacturing process (right) and sample in the mould (left)

Two percentages of paraffin and $MgB_2$ were prepared for the tests with the MOUETTE slab burn, 5% and 10 %, to represent the average of the quantities tested if the RMA slab-burner. After, it was investigated the possibility to produce grain with superior dimensions.

The MOUETTE grains have the average dimensions of 150 mm in length, 30 mm high, and 40 mm in width, in a semi-rectangular parallelepiped form, and the ULB-HRM grain is a cylinder with a combustion port of 50 mm and a maximum length of 110 mm. The 1kN fuel grain dopped with Magnesium boride was challenging, because it was the first time that an expressive quantity of the additive needed to be mixed with 1000 grams of paraffin. Various techniques were tested to figure out how to produce a more uniformed grain, and two of them showed good results. The first is to divide the amount into different fraction, and then fill it until the final shape. The other is to use a large recipient and mix for a longer time. Even for 1kN engine fuel grains the percentual amount of solvent was less than 1% of the $MgB_2$ dry weight. Figure 6 shows the paraffin grain prepared for the ULB-HRM with 5% of $MgB_2$.

Figure 6: ULB-HRM paraffin solid fuel grain doped with $MgB_2$

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### 3.1 Regression rate measurements

The calculated regression rate is the average rate determined by the diameter variation of the fuel combustion port during the total burning time, and is given by Equation 1:

$$\bar{r} = \frac{d_f - d_i}{2t_b} \tag{1}$$

The pressure traces and the recorded video helped to visualize the burning. In general, the starting burning time is from 5 to 10% of the initial maximum value of the chamber pressure, and the end of burning time represents 20 to 40% of the initial maximum value. It varies because the combustion is not similar from one test to another. The initial port diameter, $d_i$, is an input data, measured before the tests, and it is equal to 50 mm for all tests with ULB-HRM presented in this work. This helps to enable an easy and fair comparison between firings, such as the initial port diameter has a significant effect on regression rate calculations in HREs as reported in Refs. [10].

The final port diameter, $d_f$, cannot be measured directly due to the complicated (slightly deformed) fuel geometry after combustion. A more precise way to estimate the final port diameter is to use the fuel mass variation expressed by Equation 2.

$$d_f = \left[d_i^2 + \frac{4\Delta m_f}{\pi \cdot \rho_f \cdot L_g}\right]^{1/2} \tag{2}$$

The average oxidizer mass flow rate is calculated by dividing the total injected mass of the oxidizer by the burning time, in the case of the ULB-HRM, and for MOUETTE slab-burn is used a chocking orifice. These data, together with the measured fuel mass, are used to evaluate the total propellant mass flow rate. The average oxidizer-to-fuel ratio (O/F) is calculated using Equation 3:

$$\overline{O/F} = \frac{\overline{\dot{m}}_{ox}}{\overline{\dot{m}}_f} \tag{3}$$

The oxidizer mass flux is defined as the instantaneous oxidizer mass flow rate over the grain port cross-sectional area [11]. Then, its average formula is given by Equation 4, according to [12]. And for initial values are calculated using Equation 5.

$$\overline{G}_{ox} = \frac{16\overline{\dot{m}}_{ox}}{\pi(d_i + d_f)^2} \tag{4}$$

$$\overline{G}_{ox\_i} = \frac{4\overline{\dot{m}}_{ox}}{\pi d_i^2} \tag{5}$$

The combustion efficiency ($\eta^*$) is calculated by Equation 6 and it is the ratio of the characteristic velocity ($c^*_{exp}$), calculated by equation (7), and theoretical characteristic velocity, $c^*_{theor}$, obtained using a software.

$$\eta^* = \frac{c^*_{exp}}{c^*_{th}} \tag{6}$$

$$c^*_{exp} = \frac{\overline{P}_c \cdot A_t}{\overline{\dot{m}}} \tag{7}$$

For the MOUETTE slab-burn, the equations were modified taking into account the characteristics of the engine, such as the geometry of the internal motor and the solid fuel grain. Also, modifications to calculate the regression rate by the means of the burning area and the oxidizer inlet mass flux were done. All tests with the MOUETTE slab-burner used GOX (gaseous oxygen) as the oxidizer, meanwhile, for the 1kN ULB-HRM nitrous oxide ($N_2O$) was the choice.

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## 4. Results

### 4.1 Results of the tests with the MOUETTE slab-burner

Table 2 presents all the 25 (twenty-five) tests carried out using the MOUETTE slab-burner, Figure 3. The designed oxidizer mass flow rate for these tests is 50 g/s, 75 g/s, and 100 g/s, by the means of three different shocking orifices with design diameters of 1.9 mm, 2.4 mm, and 2.7 mm, respectively. The experimental values of the gaseous oxygen average mass flow rate diverged to some degree from the theoretical calculation, which results in an average of 53.7g/s, 81.1 g/s, and 95.9 g/s.

The chamber pressure (gauge pressure) varies from 0.34 bar to 6.58 bar and the burning time is from 5 to 7 seconds. The tests #13, #14, #16, #17, and #18 represent the fuel matrix doped with Magnesium diboride (additive). The test 15 and test 23, the grain geometry was changed (gran with step) and all the other tests are with pure paraffin.

Table 2: Results MOUETTE test campaign

| Test Number | Burning Time (s) | Tank Pressure (bar) | Chamber Pressure (bar) | Mass Flow (g/s) | Inlet Mass Flux ($g/cm^2s$) | Notes |
|---|---|---|---|---|---|---|
| 1 | 5.32 | 37.46 | 0.11 | 54.63 | 1.27 | Pure paraffin |
| 2 | 5.31 | 36.54 | 0.09 | 53.17 | 1.24 | Pure paraffin |
| 3 | 5.22 | 36.65 | 0.34 | 53.47 | 1.24 | Pure paraffin |
| 4 | 5.18 | 36.64 | 1.91 | 53.45 | 1.24 | Pure paraffin |
| 5 | 5.38 | 36.54 | 3.05 | 53.31 | 1.24 | Pure paraffin |
| 6 | 5.28 | 36.50 | 3.20 | 53.26 | 1.24 | Pure paraffin |
| 7 | [-] | [-] | [-] | [-] | [-] | Error in data acquisition |
| 8 | 5.56 | 36.84 | 2.75 | 53.77 | 1.25 | Pure paraffin |
| 9 | 5.25 | 37.22 | 2.88 | 54.33 | 1.26 | Pure paraffin |
| 10 | [-] | [-] | [-] | [-] | [-] | Error in data acquisition |
| 11 | 5.52 | 34.92 | 2.23 | 81.20 | 1.89 | Pure paraffin |
| 12 | 5.61 | 34.86 | 2.28 | 80.93 | 1.88 | Pure paraffin |
| 13 | 5.41 | 34.62 | 2.52 | 80.51 | 1.87 | Paraffin + additive |
| 14 | 5.64 | 34.58 | 1.78 | 80.36 | 1.87 | Paraffin + additive |
| 15 | 5.46 | 34.45 | 2.48 | 79.20 | 1.84 | Different fuel grain geometry |
| 16 | 5.58 | 35.87 | 2.49 | 83.37 | 1.94 | Paraffin + additive |
| 17 | 5.64 | 35.15 | 2.57 | 81.69 | 1.90 | Paraffin + additive |
| 18 | 5.54 | 35.00 | 2.04 | 81.38 | 1.89 | Paraffin + additive |
| 19 | 5.46 | 33.67 | 2.96 | 98.66 | 2.29 | Pure paraffin |
| 20 | 5.56 | 33.46 | 4.76 | 98.12 | 2.28 | Pure paraffin |
| 21 | 7.30 | 33.12 | 6.23 | 97.14 | 2.26 | Pure paraffin |
| 22 | 7.24 | 32.89 | 6.58 | 96.49 | 2.24 | Pure paraffin |
| 23 | 7.24 | 32.26 | 3.33 | 95.85 | 2.23 | Different fuel grain geometry |
| 24 | 5.58 | 31.62 | 4.54 | 92.80 | 2.16 | Pure paraffin |
| 25 | 5.55 | 31.31 | 4.69 | 91.94 | 2.14 | Pure paraffin |

As the scope of this work is related to the performance of paraffin and paraffin with $MgB_2$, thus, reference [8] brings a complete description of the tests with pure paraffin, and the findings of the tests with the different geometry grains are the topic of reference [12]. In this work, pure paraffin is defined as the original state that which the product is sold and delivered by the supplier, and no modifications, except melting and moulding, are done at the ULB/ATM department.

Tests #7, #10, and #14 were not taken into account in this work due to technical problems with the data acquisition system and the control system of the test bench. In tests #13 and #16 paraffin was mixed with 10% of $MgB_2$, namely 10MgB*p*, and tests #17 and #18 have paraffin and 5% of $MgB_2$, 5MgB*p*.

Taking into account that for low pressure and low oxidizer mass flow rates the regression rate is a function of those variables, to compare the tests with the grains 10MgB*p* and 5MgB*p* and the ones with pure paraffin, it was considered the tests #8, #11, and #12 that have chamber pressure values around 2.5 bar ($\pm$ 0.5 bar). Table 2 also indicates that the average regression rate for the tests with pure paraffin ranged from 0.19 mm/s to 0.36 mm/s, relatively closer to the tests with paraffin and 10% of $MgB_2$, from 0.26 mm/s to 0.31 mm/s, and paraffin with 5% of $MgB_2$, from 0.25 mm/s to 0.39 mm/s.

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However, the $c*$ efficiency (η*) is higher for the test with the higher quantity of additive and practically equal for the tests with 5MgB*p*. Taking into account the η* (Equation 6) and test 8 (with pure paraffin) the pressure in the chamber was higher (2.75 bar) in comparison with test 13 (2.52 bar), 10MgB*p*, and the calculated efficiency was 34% and 35%, respectively.

The average chamber pressure of tests #8, #11, and #12 are shown in Figure 7. Figure 8 presents the results for the tests #13, #16, #17, and #18. All the graphs showed similar behaviour and it is possible to infer that most of the time the pressure in the combustion chamber did not stabilize, even in a situation of chocked oxidizer flow. Modifications in the test procedures are in progress to avoid this operational limitation. Figure 9 shows a characteristic pressure drop in the chocked orifice and the combustion chamber.

Table 3: Comparison between dopped fuels and pure paraffin

| Test Number | Chamber Pressure [bar] | $\dot{m}_{fuel}$ (g/s) | $\dot{r}$ (mm/s) | $\eta^*$ | Notes |
|---|---|---|---|---|---|
| 08 | 2.75 | 1.26 | 0.36 | 34 % | Pure paraffin |
| 11 | 2.23 | 1.04 | 0.30 | 19 % | Pure paraffin |
| 12 | 2.28 | 1.48 | 0.19 | 19 % | Pure paraffin |
| 13 | 2.52 | 0.98 | 0.26 | 35 % | GOX / Paraffin & 10 % $MgB_2$ |
| 16 | 2.49 | 1.14 | 0.31 | 20% | GOX / Paraffin & 10% $MgB_2$ |
| 17 | 2.57 | 1.42 | 0.39 | 21 % | GOX / Paraffin & 5% $MgB_2$ |
| 18 | 2.04 | 0,91 | 0.25 | 17 % | GOX / Paraffin & 5% $MgB_2$ |

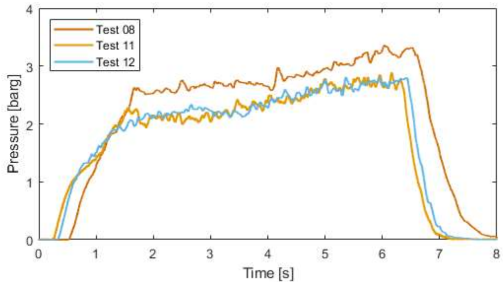


Figure 7: Tests #8, #11, and #12 – pure paraffin

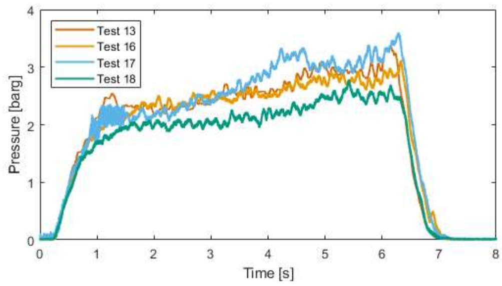


Figure 8: Tests #13 and #16 (10MgB*p*); #17 and #18 (5MgB*p)* – Paraffin + additives

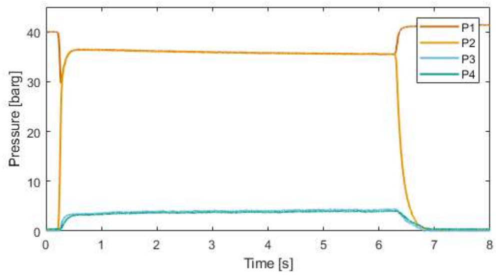


Figure 9: Feed-system pressure budget, test 8

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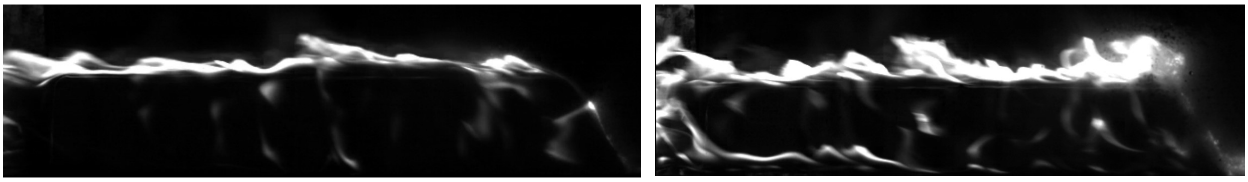
In Figure 9, P1 is the pressure in the gaseous oxygen line, near the oxidizer test bench feed system entrance, P2 is the pressure before the orifice, P3 is the pressure after the orifice, and P4 is the pressure near the pre-combustion chamber entrance. For this test, the average values of the pressures P3 and P4 are very close, 3.66 bar and 3.42 bar, respectively.

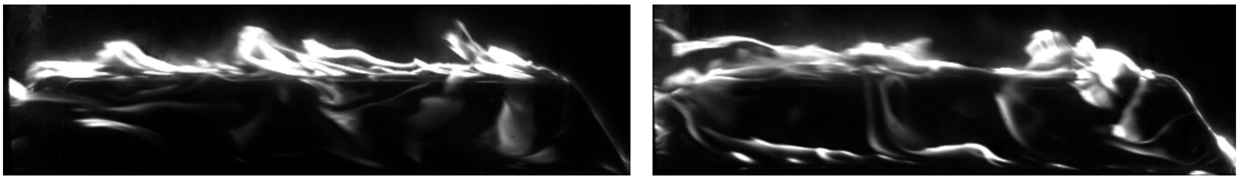
One of the advantages of the MOUETTE slab-burner is the possibility of visualizing the combustion chamber. For this set of tests (Table 3), it was used a Photon FASTCM SA4 highspeed camera together with a CH* filter. The sample rate is 3000 frames per second, with a resolution of 512x352 pixels. Two LED light source was used to obtain the best possible instantaneous picture.

The discussion and analysis of the visualization results are out of the scope of this paper, but the treatment of the images is under process and a detailed analysis will be presented in a near future. In order to illustrate the quality of the images produced, Figure 10 shows two instantaneous of test 12 (pure paraffin) where it is possible to see the development of the combustion process in two different moments during the test. Figure 10(a) shows the moment at 3.07 seconds and Figure 10(b) the instant at 5.09 seconds. On the other hand, Figure 11 presents the instantaneous for test 16, using 10MgB*p,* and Figure 12 for test 17, with 5MgB*p*. Figure 11(a) shows the photo at the moment at 3.06 seconds and Figure 11(b) at 5.3 seconds. Approximately, the same was done for test 17; Figure 12(a) is in the time 3.12 seconds and 12(b) 5.33seconds. All the films have a total duration of 7.57 seconds.



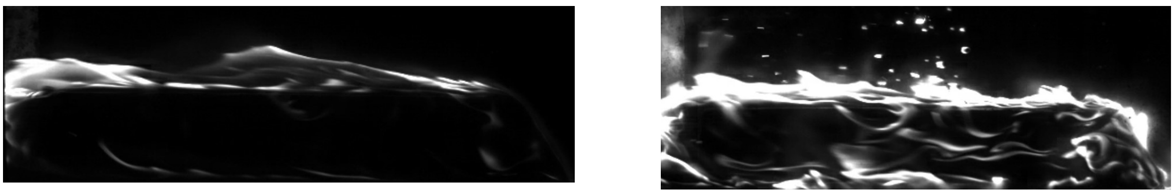
(a) (b)

Figure 10: Visualization of Test 12 (pure paraffin)



(a) (b)

Figure 11: Visualization of Test 16 (10MgB*p*)



(a) (b)

Figure 12: Visualization of Test 17 (5MgB*p*)

By the analysis of all the movies filmed with the high-speed camera, a specific periodical oscillation was observed for each test. As at the moment the MOUETTE data acquisition system has only ordinary pressure transducers, a modification is planned to use a Kistler piezoelectric pressure transducer, a fast response sensor to permit spectral analysis of the pressure-time history, but it requires an alteration of one of the MOUETTE sensor adapters (under

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study). This modification allows to determine the dominant frequencies of the combustion chamber and compare with the fast-speed camera image pulsing, to study if any correlation is possible. Another interesting observation that the visualization permits is related to test 17, Figure 12(b), where is possible to observe various macroscopic paraffin droplets, and this test presented a higher regression rate in comparison with all the other tests analysed, but not the higher efficiency. This remark shows that a study about the size of the entrained fuel droplets can be valid, as it has an important impact not only on the regression rate but also on the combustion efficiency.

## 4.2 Results of the tests with the 1kN ULB Hybrid Rocket Motor

After the test with the MOUETTE slab-burner, which showed a good agreement with the preliminary study using the RMA slab-burner [7], and it showed on small scale some advantages to using Magnesium diboride as an additive, three tests were carried out with the 1kN ULB-HRE. The quantity of Magnesium diboride define for the tests is 5% related to the baseline pure paraffin grain. Additionally, a test with pure paraffin was used to set the test parameters. Table 4 presents the test conditions and Table 5 is from reference [9] that uses the same motor and injector.

The analysis of the results shows that for the 1kN motor scale the solid fuel grain doped with 5% of Magnesium diboride (5MgB*p*) can increase the solid fuel regression rate. However, during the tests with magnesium diboride samples the fuel was consumed during the test, and also part of the PVC (polyvinyl chloride) grain casing was consumed as well. Once the PVC regression rate is 0.686 mm/s [13], it is possible to conclude qualitatively that the regression rate calculated for the paraffin doped with 5% $MgB_2$ (5MgB*p*) is underestimated. Figure 13 shows the condition of the pure paraffin grain after the burning, and Figure 14 shows the solid fuel grain of test 2 (5MgB*p*, Table 4). The burning time for each case was defined by the automatic test sequence and estimated as 5.1 seconds for both tests, and the combustion port for all the cases is 50 mm.

Table 4: Results for the test with the 1kN ULB-HRM

| Test Number | Propellant | $t_b$ [s] | $\bar{\dot{m}}_{ox}$ [kg/s] | $P_c$ [bar] | $\bar{G}_{ox}$ [kg/m²s] | $\bar{\dot{r}}$ [mm/s] | O/F | F [N] |
|---|---|---|---|---|---|---|---|---|
| 1 | Pure Paraffin | 5.1 | 0,432 | 16.7 | 78.7 | 6.12 | 2.7 | 952 |
| 2 | Paraffin + 5% $MgB_2$ | 5.1 | 0,508 | 20.3 | 69.9 | 9.06[a] | 2.8 | 1158 |
| 3 | Paraffin + 5% $MgB_2$ | 5.1 | 0,508 | 20.3 | 63.6 | 9.97[a] | 3.5 | 1158 |

[a] Considering the entire test time, that included also the burning of the PVC (polyvinyl chloride) used as grain casing and chamber thermal protector.

Table 5: Database test with ULB-HRE [9], *with modifications*

| Test Number | Propellant | $t_b$ [s] | $\bar{\dot{m}}_{ox}$ [kg/s] | $P_c$ [bar] | $\bar{G}_{ox}$ [g/cm²s] | $\bar{\dot{r}}$ [mm/s] | O/F |
|---|---|---|---|---|---|---|---|
| SH3-1 | Pure Paraffin | 5.3 | 0,538 | 22.8 | 14.9 | 7.33 | 3.5 |
| SH3-2 | Pure Paraffin | 5.2 | 0,543 | 23.8 | 15.1 | 7.22 | 3.6 |
| SH3-3 | Pure Paraffin | 5.3 | 0,538 | 24.4 | 14.4 | 7.38 | 3.5 |

The result of the test with pure paraffin, test 1, is compared with the ULB/ATM Department database, reference [9] with the same hybrid motor. The main difference between the test is the data acquisition system and the automatic test routine. Also, the pressure sensors and thermocouples for the test presented here are new, but on the same scale and brand as the tests presented in Table 5. The regression rate with pure paraffin, test 1, is 6.12 mm/s and combustion chamber pressure of 16.7 bar, though the test conditions were the same as the test presented in Table 5. Figure 15 shows a comparison between the chamber pressure for the test with pure paraffin and paraffin dopped with Magnesium diboride.

The paraffin doped with 5% Magnesium diboride has a regression rate of 9.06 mm/s and 9.97 mm/s for test 2 and test 3, respectively (Table4). Comparing the regression rate for these tests (# 2 and #3) with the reference [5], where the chamber pressure is higher, it is possible to affirm that the regression rate of the 5MgB*p* grain is superior. Regardless of the analysed case, in test 1 with pure paraffin or the database (Table 5) the regression rate of the 5MgB*p* grain is higher than the one with pure paraffin.

It is important to notice that the regression rate calculate for test 2 and test 3 the burning time englobes the combustion of the paraffin doped with $MgB_2$ and the PVC grain casing. Since the regression rate of PVC is more than 9 (nine) times lower than that of paraffin-based fuels (Table 4 and references [2, 9, 10, 13, and 14]), additional tests are needed to determine the 5MgB*p* grain average regression rate.

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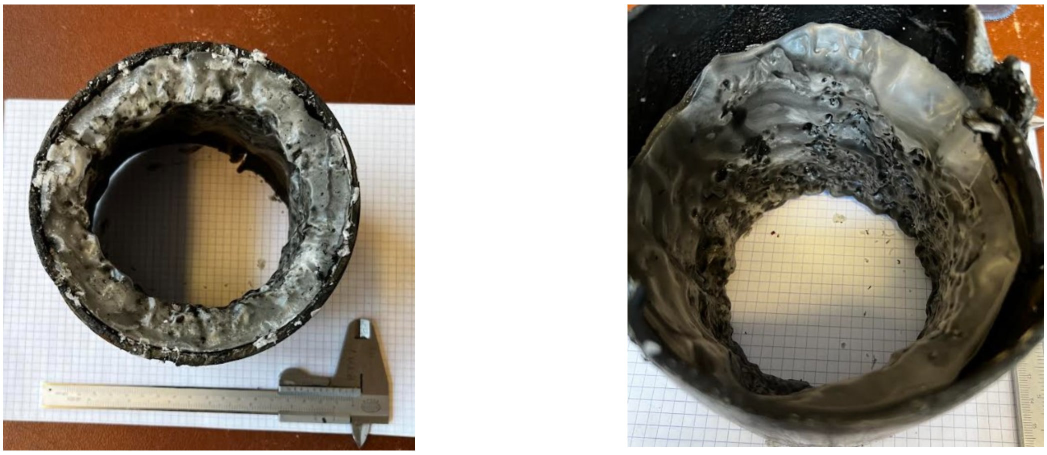

(a) (b)

Figure 13: Pure paraffin solid fuel after test 1, burning time of 5.1 seconds

(a) (b)

Figure 14: 5MgB*p* grain; paraffin +5%$MgB_2$ solid fuel after test 2, burning time of 5.1 seconds

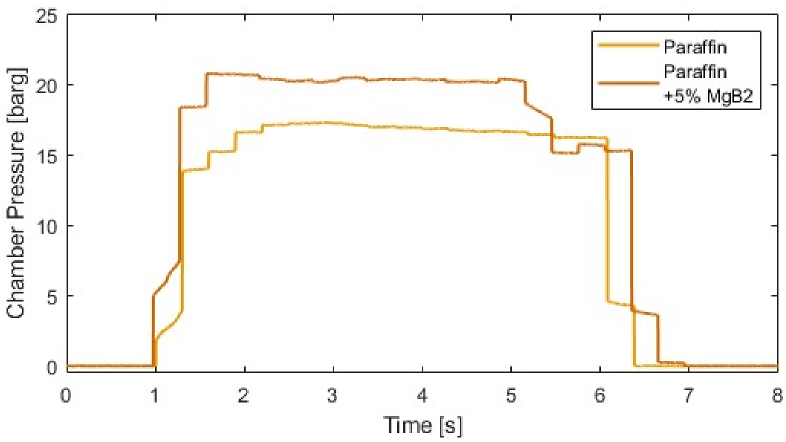


Figure 15: Chamber pressure for the test 1 and test 2

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Nowadays, the Aero-Thermo-Mechanics Department is redesigning the 1kN combustion chamber and improving the data acquisition system, and incorporating another logic for the data acquisition routine, based on LabView software, to increase the quality of the data collected.

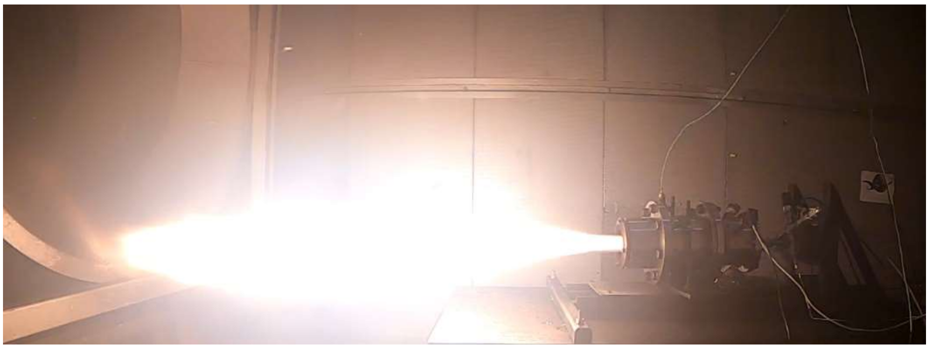

Figure 16: 1kN ULB-HRM during the test 2, Table 4

## 5. Conclusions

Boron has an extensive application prospect in the field of aerospace propulsion, such as chemical rockets and ramjets. Among the common solid and liquid fuels for the aerospace industry, boron has the highest volumetric calorific value, 137.7 kJ/cm$^3$. The challenge for the application is that boron particles tend to agglomerate, having lengthy ignition delays and very low combustion rates. In addition, the oxidation product of boron has a low melting point (450ºC) and high boiling point (1860ºC), which leads the boron particles to be wrapped in the liquid oxidation film during combustion, which hiders the permeation of ambient oxygen and effects the combustion efficiency. However, unlike boron, Magnesium diboride ($MgB_2$) burns completely when ignited in an oxidizer atmosphere [15 - 18].

A preliminary study of the Aero-Thermo-Mechanics Department (ATM) at Université Libre de Bruxelles (ULB) and the Belgium Royal Military academy (RMA) indicates that Magnesium diboride, $MgB_2$, is a candidate for paraffin-based fuels performance enhancement agent. The main advantage of using Magnesium diboride lies in the fact that this additive is more stable and easier to handle than other metal hydrides, such as Lithium Aluminium Hydride and $MgH_2$ [7]. This works aimed to extend the expertise and experimental database of paraffin-based fuels doped with Magnesium diboride on two different scales, using the ULB/ATM MOUETTE slab-burner and the 1kN ULB hybrid rocket motor.

A technique to produce hybrid rocket solid fuel using pure paraffin and paraffin doped with Magnesium boride was improved for the samples used in the MOUETTE slab-burner and developed for the lab-scale 1kN ULB/ATM hybrid rocket motor. The approach produced high-quality grains without cracks or deboning. The tests with the MOUETTE slab-burner had GOX (gaseous oxygen) as oxidizer and nitrous oxide ($N_2O$) for the 1kN engine. The fuel was pure paraffin (baseline) and paraffin dopped with 5% and 10% of $MgB_2$. Homogeneous samples for both hybrid rocket motors were manufactured, however, in all the cases, a commercial solvent was needed. For the MOUETTE slab-burner, the quantity was inferior by 0.5% (in $MgB_2$ dry weight) and for 1kN ULB-HEM up to 1%. A goal for the next work is to engage in reducing the quantity of the solvent. A try to produce grains without the commercial solvent was unsuccessful and resulted in an excessive concentration of the additive in the base of the fuel mould by gravitational settling.

A set of tests using the MOUETTE slab-burner, at low oxidizer mass flow rate and low pressure were carried out. In these tests, the pressure fluctuates around 2.5 bar, and at this condition, the regression rate is impacted. But it was possible to observe that the tests with the metal additive improve the efficiency of the combustion ($\eta^*$), and the limits of the regression rate. Since at this level of pressure the regression rate is impacted by the chamber pressure, additional tests are planned to be carried out with MOUETTE to verify the tendency of the average regression rate and combustion efficiency ($\eta^*$) at a higher level of chamber pressure (up to 7 bar, [8]).

Two firing tests using ULB lab-scale hybrid rocket motor (~1kN) were executed to study the behaviour of the solid fuel in this hybrid rocket operation conditions. Table 4 presents the results of those tests and also the test with the pure paraffin (baseline) fuel. When comparing the final condition of the fuel grains (Figure 13 and Figure 14), for the same

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burning time, it is possible to notice a qualitative tendency of solid fuel regression rate improvement. An attempt to estimate the regression rate of the solid fuel grain dopped with 5% $MgB_2$ (5MgB*p* sample) indicates values around 9 mm/s, superior to the baseline pure paraffin, Table 4, and Table 5 (ULB/ATM Department database, [9]). Nevertheless, the samples 5MgB*p* (test 2 and test 3) were completely consumed during the firing, and also part of the polyvinyl chloride (PVC) used as the grain casing. As the PVC burns slowest than the fuel [13], modifications in the experimental apparatus are in progress to collect more information about the fuel's efficiency. The $c^*$ efficiency ($\eta^*$) for pure paraffin was calculated as 0.94 (94%) and for the fuels with additives 0.9 (90%), but it is important to notice the impact of the PVC low performance burning rate on the test #2 and #3.

The next steps of the research are focusing on the revision of the data acquisition software to improve that sample rate and the integration of a piezoelectric sensor to study the oscillations of the pressure in the combustion chamber. Simultaneously, a new battery of tests is planned to verify the impact of the different combinations of the paraffin and additive and the determination of the regression rate coefficients.

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