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RESEARCH ARTICLE

Investigation of paraffin combustion in a hybrid rocket slab burner

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Abstract

Hybrid rocket engines (HREs) are a category of chemical rocket propulsion systems in which the two propellants are stored in different states of matter. They have been often overlooked due to their lower performance with respect to conventional liquid rocket engines, and increased complexity over solid rocket motors. Recently, HREs are gaining new momentum for small launcher applications, as their performance is coupled with intrinsic safety, throttle-ability, flexibility and low cost, promising advantages when aiming to build a cost-effective space transportation system.

Taking advantage of a hybrid rocket slab burner, an experimental HRE where a two-dimensional solid fuel grain is tested in a combustion chamber with optical access, the combustion behavior of paraffin wax with oxygen has been investigated, measuring the regression rate of the fuel and acquiring high-speed video recordings of the combustion.

Multiple tests have been performed under different oxidizer mass flux and combustion chamber pressure conditions, grouped into four main experimental campaigns, providing insights into the fuel regression rate dependence on these parameters, allowing to trace the experimental correlation between oxidizer mass flux and fuel regression rate. Then, taking advantage of the video recordings of the combustion, phenomena such as liquid droplets entrainment have been visualized, as well as a qualitative description of the combustion behavior at different combustion chamber pressure and oxidizer mass flux.

The effect of the oxidizer mass flux on the regression rate of the paraffin slab has been assessed, and the experimental data proved to be in accordance with the predictions coming from literature, as an

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increase in mass flux correlates with an increase in the measured regression rate. The effect of pressure at low mass fluxes, however, has not been clearly assessed in the study, and further investigations are required for future studies.

Keywords
Hybrid Rocket Engines, Paraffin Fuel, Combustion Visualization, Regression Rate Measurements



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Introduction

A hybrid rocket engine (HRE) is a chemical rocket propulsion system based on the combination of a liquid oxidizer and a solid fuel. While being first demonstrated in 1933 in the Soviet Union[1], the development of the technology fell behind the two most efficient alternatives, liquid rocket propulsion and solid rocket propulsion, and most of its peculiarities and drawbacks have yet to be fully understood and overcome[2].

Nevertheless, the research on this type of technology never halted, due to the promising advantages it offers in exchange for a compromise in performance. These advantages are simplicity, safety, and cost-effectiveness.

And it is mainly the perspective of a limited cost of manufacturing and operation that gave new momentum in recent years to the development of hybrid rocket propellant based launchers and spacecrafts[3].

Hybrid rocket slab burners

When developing a new rocket engine, the accurate modeling of the internal ballistics of the combustion chamber is fundamental to design a reliable system, and for propulsion systems using a solid propellant the regression rate is one of the main drivers. In particular, when developing a new propellant formulation, it is convenient to test small samples in dedicated burners to understand their behavior before scaling up[4]. In Solid Rocket Motors (SRMs) this is typically done in strand burners, where a small propellant sample is ignited at controlled chamber pressure, and its consumption over time is measured to determine the regression rate. Strand burners are convenient for SRMs, where fuel and oxidizer are mixed together, but in HREs an external supply of oxidizer is necessary to sustain the combustion. A solution for this research requirement is found in hybrid rocket slab burners, which present the main characteristics of a HRE, namely an oxidizer feed system, an ignition system, a combustion chamber with oxidizer injection and a nozzle. Compared to their conventional counterparts, the main difference is in the fuel grain, which is not a classical cylindrical perforated grain, but a *slab*, which is by definition a *thick, flat piece of a solid substance*.

While the regression rate could be measured in a simpler cylindrical grain using a radial burner[5], the main advantage of the slab burner is the bi-dimensional flow field that is created over the flat fuel surface. The introduction of an optical access positioned parallel to the direction of the oxidizer, and normal to the slab surface, allows the visualization of the boundary layer and the diffusion flame developing over the solid fuel surface in a bi-dimensional condition which is key for the experimental verification and deduction of internal ballistics modeling of fuel regression[6].

An example of a fuel slab used for the tests discussed in this article is shown in Figure 1, presenting a forward facing ramp for flameholding purposes.



Figure 1. Paraffin fuel slab.

Experiments with paraffin-based fuels

Thanks to the entrainment mechanism, paraffin-based fuels allow to have a high regression rate without compromising the simplicity of HREs[7]. In particular, a high regression rate allows to use single port fuel grains, with a high volumetric loading and reduced complexity and inert mass requirements. Moreover, paraffins are non-toxic and relatively environmentally friendly, with a good specific impulse[8]. The main drawbacks that need to be tackled are, however, a low combustion efficiency, a low structural resistance and the proneness to low frequency combustion instabilities, aspects that can be addressed by introducing additives in the paraffin fuel formulation[9].

Visualization experiments with a slab burner are particularly interesting for paraffin-based fuels due to the peculiar combustion mechanics, given by the liquid film formation and the droplets breakout and entrainment phenomena. Hybrid rocket slab burners have been used to perform investigations on the effect of additives and different liquid layer viscosity on the combustion. The experiments differ for the visualization techniques, typically high-speed video acquisitions, and operating pressure and mass flux. The rest of the section gives an overview of recent slab burner experiments carried out for paraffin-based fuels.

Kim *et al.*[10], at the Korea Aerospace University, performed optical investigations of paraffin fuel blended with low density polyethylene (LDPE), to visualize liquid layer entrainment phenomena with hot gas injection, without a combustion reaction, and then to visualize the flame of paraffin, paraffin blended with LDPE and pure high density polyethylene (HDPE), providing qualitative results of the fuel type influence on the flame shape.

Nakagawa *et al.*[11], from the Tokai University, performed combustion experiments using gaseous oxygen as oxidizer and both pure paraffin and paraffin mixed with ethylene-vinyl acetate (EVA) as fuels to change the viscosity of the melted layer. They used high speed videos to experimentally demonstrate the presence of a melted fuel layer and the entrainment of paraffin droplets and derived a relation between the viscosity of the melting layer and the regression rate.

Chandler *et al.*[12] from Stanford University acquired high speed videos of different fuels (Paraffin, HDPE, HTPB among others) burning with gaseous oxygen with a pressure up to 5 bar, performing qualitative investigations of liquid entrainment, droplets visualization and flame bursting. Jens *et al.*[13,14] continued the work by performing experiments with different fuels with a pressure up to 17 bar and a higher mass flow rate.

Kobald *et al.*[15] from the German Aerospace Center performed high speed visualization and Z-type schlieren imaging of paraffin burning at atmospheric pressure conditions. They also tested paraffin mixed with stearic acid to change the viscosity of the liquid layer. They later introduced Proper Orthogonal Decomposition (POD) and Independent Component Analysis (ICA) techniques to analyze the luminosity field of the frames acquired with the high speed videos, to automatize the data analysis of the videos and acquire wavelengths and frequencies information about the flame patterns[16]. Petrarolo *et al.*[17–19] improved the quality of the acquired videos, and applied the aforementioned techniques to investigate Kelvin-Helmholtz instability at the liquid layer, the relationship with viscosity and the droplets entrainment mechanism.

Wada *et al.*[20] from Akita University performed combustion experiments of different polymers and paraffin fuels with a chamber pressure up to 20 bar. The slab burner configuration adopted for their test bench is a vertically mounted set up, with two opposing slabs mounted in parallel with the fuel flow. For the combustion of paraffin at high-pressure range they observed that both the number and size of droplets entrained are independent of the pressure.

Paravan *et al.*[21] at Politecnico di Milano carried out entrainment visualizations of paraffin blended fuels at atmospheric pressures and in cold flow to identify the droplet breakout and entrainment mechanism. In their setup, the fuel is not ignited, but melted using an electrical resistance. They observed the primary and secondary break-up mechanisms of pure paraffin and paraffin with the addition of polymers to increase the mechanical properties.

Bertoldi *et al.*[22] at Université libre de Bruxelles (ULB) used a slab burner to investigate the effect on performance of a paraffin slab doped with magnesium diboride (MgB_2).

At the University of Calgary, Dunn *et al.*[23] visualized burning paraffin-based fuels in ambient pressure, inserting wedges to change the pressure gradient inside the combustion chambers. From image reconstruction they performed measurements of the regression rate with different pressure gradients in the chamber and at different points of the fuel grain.

At the Kyushu Institute of Technology, Ozawa *et al.*[24] realized a slab burner to investigate the effect of the test bench orientation on the combustion of paraffin-based fuels. With a high-speed camera, they visualized the diffusion flame at atmospheric chamber pressure both in a horizontal and in a vertical burner configuration, to asses if gravity effect impacted on the entrainment and ballistics of droplets. They observed that a body force up to 10 g doesn't affect the entrained droplets internal ballistics, but has an impact of the mass flux of the melted layer.

Budzinski *et al.*[25] from the University of Buffalo realized a slab burner to study the radiation heat transfer in paraffin wax fuel grains, applying two-color pyrometry to the high speed images.

Liu *et al.*[26] performed several studies on the boundary layer combustion of paraffin painted black with a 1% of carbon powder and using gaseous oxygen as oxidizer. They also performed experiments doping the fuel with catocene and copper chromite and cobalt stearate.

Experimental methods

An optical access slab burner, called MOUETTE (Moteur OptiqUe pour ÉTudier et Tester Ergols hybrides), has been designed at ULB to investigate the combustion behavior of HRE fuels[27,28]. The combustor features a modular design, so the components can be modified according to the different research needs, and can be also used as small-scale HRE test bench. The chosen oxidizer is gaseous oxygen (GOX), with a mass flow rate that can be adjusted using a chocking orifice in the feed lines and regulating the pressure of the gas fed from the reservoir. The ignition of the solid fuel slab is achieved with a pyrotechnic squib, and the pressure in the combustion chamber is maintained using a convergent nozzle with a graphite throat insert. Pressure measurements are acquired both in the combustion chamber and in the feed lines, as well as the oxygen flow temperature. The pre-combustion chamber is fitted with two honeycombs and a wire mesh screen, to reduce the oscillations of the flow during testing.

The test section has two parallel quartz windows that can be used to perform high-speed video acquisitions of the fuel combustion, also with chemiluminescence and schlieren imaging techniques. For the tests investigated in this article, a Photron FASTCAM SA4 500K-M1 high-speed camera has been used.

The nominal maximum operating conditions of the MOUETTE slab burner are listed in Table 1, while a photograph of a test is shown in Figure 2.

The first step in performing a test with the MOUETTE is the definition of the test parameters. In particular, the variables

Table 1. Maximum operating conditions of MOUETTE.

Combustion chamber pressure	10 bar
Oxidizer mass flow rate	100 g/s
Oxidizer mass flux	50 kg/m²s
Burning time	10 s

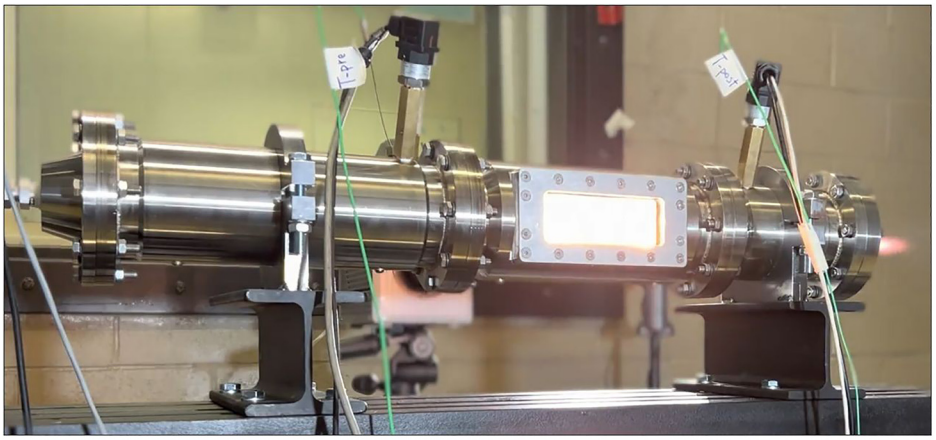

Figure 2. Photograph of a MOUETTE test.

that can be controlled are the test duration, the rate of injected oxidizer, and the nozzle throat.

After the parameters have been set, the fuel slab is weighed, and the dimensions are measured and reported.

The tests discussed in this article are taken from different campaigns performed with a paraffin fuel slab made in Tudamelt 52/54, produced by Hansen & Rosenthal group. The material is supplied in white pellets, with a melting temperature ranging between 52 and 54 °C, and a density of 920 kg/m^3. The slabs are realized through casting in a dedicated mold. A black pigment is incorporated into the paraffin at a concentration of 0.5% by weight, to enhance the radiation absorption of the fuel and liquid droplets surface. Before testing, the lateral and rear faces of the slab are protected with a coating of Paraloid B-72, an inhibitor also used for SRMs[29]. The typical fuel slab has a forward facing ramp of 30°, a base length of 130 mm, a width of 75 mm and a height of 30mm, for a mass of approximately 210 grams.

The tests are enumerated with letters from A to D according to the test campaign in which they have been performed, as in Table 2.

The typical test sequence starts with the ignition transient, where the pyrotechnic igniter generates the heat required for the combustion to start, followed by the main combustion phase. After the defined test duration, the oxygen valve closes, leading to the shut-off transient. Finally, a nitrogen flow purges the combustion chamber and extinguish the flame.

At the end of the test, the pressure in the feed system is discharged, the nozzle is removed and the windows are disassembled and cleaned from soot and paraffin deposits. The fuel grain is removed, as well as the unburnt paraffin residuals which typically remain in the post-chamber and on the trailing edge of the grain holder, a phenomena well-known in experimental research on paraffin combustion[24,30–32]. The mass of the slab and residuals is taken, and the final dimensions of the slab are recorded, in order to estimate the average burning area, and the different regression among the faces. The residuals, collected by accurately scraping the grain holder and the post-chamber, typically account for 10–15% of the total final mass of the fuel. The slab burner can then be prepared for another test.

Table 2. Overview of MOUETTE experimental campaigns.

Time period	Test Code	Number of tests
Spring 2022	A	18
Spring 2023	B	15
Winter 2023	C	6
Spring 2024	C	4
Spring 2024	D	16

Excluding the high-speed videos, the main data output of a test are the pressure readings in the feed system and in the chamber, acquired with a sampling frequency of 1 kHz, with an example given in Figure 3.

In the plot, P1 is the pressure reading upstream of the oxidizer main valve, P2 is the reading upstream of the choking orifice, and Pc is an average between the readings of the sensors in the pre-chamber and post-chamber. P2 value is lower than the value of P1, due to the pressure losses in the pipes. The effect of the choking orifice can be noticed due to the high pressure drop ΔP between P2 and Pc.

The first value that is extrapolated from these data is the burning time t_b, which has to defined taking into account the

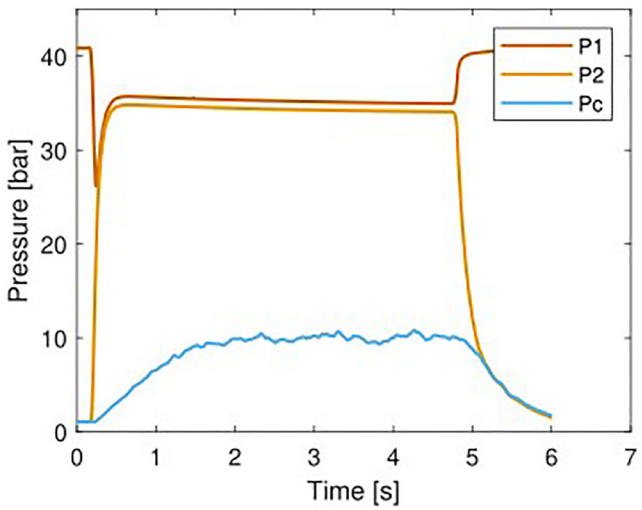

Figure 3. Measured pressure curves for test B08.

transients due to the ignition and shut-off of the system. The initial and final time instants used for the calculation are based on the observation of the ascending and descending peaks of the combustion chamber pressure. The definition of burning time is not standardized, and there are different methods that can be adopted to define the actual duration that have to be selected according to the dynamics of the HRE[33,34].

Karp and Jens[35] provide an overview of five different methods commonly adopted in literature, and some indication to select the method that is less prone to errors, depending to the test dynamics, which can be coupled with the methodology of Frederick *et al.*[36] to address the resulting uncertainty due to the different burning time definition.

Long ignition and shut-off transients have been observed in the MOUETTE, constituting a large portion of the total test duration, especially in case of slow ignition. For these considerations, the method selected is based on the average value of the combustion chamber pressure measured in the quasi-steady state period. The method is not suitable for large pressure variations during testing, but this is not the case for the MOUETTE tests. In particular, the initial value of t_b is selected when the pressure rises over a predefined threshold of the average value of Pc, and the final point when it decreases under that value. Thresholds commonly selected in hybrid rocket testing when adopting this t_b definition lies between 50%[36], 70%[37], 90%[35] and 95%[38]. Due to the slight pressure variation over the quasi-steady state testing time and to exclude the long ignition transients, the more conservative threshold of 90% has been selected.

Once the burning time is defined, the average pressure values during the firing test can be estimated as well. The average oxidizer mass flow rate $\dot{m}_{ox}$ is calculated with the equation for the choking orifice (Equation 1):

Where γ is the heat capacity ratio of oxygen and ρ_0 its density upstream of the orifice, P_0 the pressure of the flow upstream of the orifice, A the area of the orifice and c_D the discharge coefficient, experimentally characterized to a value of 0.6.

$$\dot{m}_{ox} = c_D A \sqrt{\gamma \rho_0 P_0 \left(\frac{2}{\gamma+1}\right)^{\left(\frac{\gamma+1}{\gamma-1}\right)}}$$

The oxidizer mass flux G_{ox} is then calculated as follows:

$$G_{ox} = \frac{\dot{m}_{ox}}{A_p - h_s w_s}$$

Where the denominator is the cross-section of the combustion chamber traversed by the gas flow: A_p is the empty section of the chamber, minus the section of the fuel slab normal to the flow direction, calculated using the height h_s and the width w_s. The value of A_p is 0.004227 m^2.

The second main output of a MOUETTE test is the high-speed video recording of the combustion.

To set-up the camera, several tests have been carried out to define the best parameters. The main parameters that can be adjusted are the frame rate, the lens aperture, the shutter speed and the resolution. Moreover, a camera filter can be used, in order to reduce the amount of light coming into the lens, or to allow only certain wavelengths to penetrate the lens.

For what concerns the camera used, the duration of a video is limited by the memory of the camera, and both the frame rate and the resolution affect the maximum duration that can be recorded, therefore a trade-off had to be done to be able to cover the full duration of the test.

The lens used for the camera is a Nikon 50mm f/1.2, a manual focus lens with a focal length of 50 mm, a maximum aperture of f/1.2 and a minimum of f/16. The test section is not illuminated, all the light that is captured by the high-speed camera comes from the flame itself. Therefore, to ensure the correct exposure of the video at the desired frame rate, the shutter speed and lens aperture have to be accurately tuned.

Through a calibration process performed before the tests, the conversion factor from pixel to mm can be estimated and used for the analysis.

After a test, the high-speed videos are divided in single frame sequences and then post-processed. A typical image that can be acquired from the combustion of a paraffin slab is given in Figure 4, with oxidizer flowing from left to right. On the left side of the image there is the leading edge of the slab, constituted by a forward-facing ramp that acts as flame holder. The trailing edge of the slab is harder to detect due to the recirculation zone that forms after the backward facing step. In general, the observed flame structures are highly oscillating.

Results discussion

Selected tests performed in the campaigns listed in Table 2 are discussed in this section, with the objective of providing

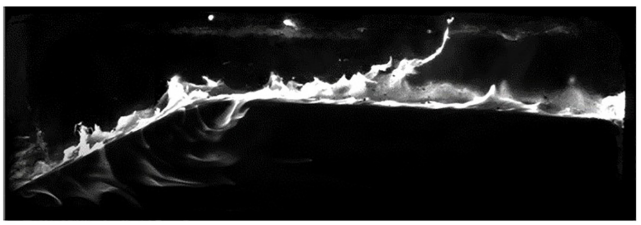

Figure 4. Combustion of paraffin in the MOUETTE slab burner.

an overview of the regression rate as function of the oxidizer mass flux, and to describe the phenomena observed in the combustion of paraffin. A visual comparison between a new slab and a burnt one is given in Figure 5 and Figure 6. After combustion, the length and height reduce, while the width is less affected, as the lateral surfaces are coated with the polymer.

In general, after the firing all the sharp edges of the slab are smoothed, in particular the top of the forward facing ramp and the top of the backward facing step. These correspond to the inlet and outlet zones of a typical hybrid rocket fuel grain, and in these zones there is a larger consumption of fuel. The increased recirculation and mixing has been observed to affect the regression rate at the entrance of fuel grains[39,40], and the backward facing step at the exit of the fuel grain has as well a beneficial effect on mixing and therefore an increased regression rate[41,42]. Moreover, the bottom of the forward facing ramp, the leading edge of the slab, has an uneven consumption along the lateral axis, with the center of the edge more burnt than the extremities. This phenomenon has been observed in all the tests, and the shape is consistent with the velocity profile of a fully developed turbulent flow in a pipe[43], suggesting that a higher oxygen flow velocity translates to a higher fuel regression.

The regression rate is calculated using the mass loss method, which is based on the variation of the fuel mass measured before and after the test, Δm_f. More precisely, what can be calculated using this method is the space and time averaged regression rate $\bar{\dot{r}}$, hereafter denoted simply as $\dot{r}$.

For a conventional fuel grain with a single circular port, this value can be obtained by measuring the variation of the port diameter over the burning time:

$$\dot{r} = \frac{D_f - D_i}{2t_b}$$

where D_i and D_f are respectively the initial and final port diameter. As the evolution of the diameter is not perfect due to the turbulent nature of the combustion phenomena, an equivalent

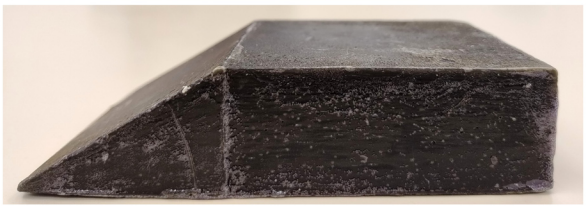

Figure 5. Paraffin fuel slab before testing.



Figure 6. Paraffin fuel slab after testing.

final diameter is calculated by measuring the total fuel mass variation Δm_f of the test using the following equation:

$$D_f = \sqrt{D_i^2 + \frac{4\Delta m_f}{\pi \rho_f L_f}}$$

where ρ_f is the density of the solid fuel and L_f the length of the grain.

The adaptation of this method to a slab burner is not trivial, as the burning area is not the conventional cylindrical port. Therefore, a final equivalent diameter cannot be defined easily. For providing an estimation, a different method has been adopted. Starting from the definition of fuel mass flow rate, where A_b is the burning surface of the fuel slab:

$$\dot{m}_f = \frac{\Delta m_f}{t_b} = \rho_f \dot{r} A_b$$

a space and time average $\dot{r}$ can be estimated knowing an average burning surface. To define the value of A_b to use, some considerations have been made. First, the fuel slab geometrical features are measured before and after each test. However, it has been noticed by observing the recorded videos of the tests, that the melting of the paraffin happening at the end of the test, between the shut-off transient and the purge, affects the final shape of the slab and therefore the measurable dimensions. The deformation can't be accurately predicted, therefore the average between initial and final area cannot be used. Moreover, it must be remembered that not all the slab surfaces are subjected to combustion in the same manner. For the slabs investigated, the lateral and rear surfaces are covered with the polymer, and the bottom of the slabs, except for non-nominal tests where the slab detaches from the holder and burns underneath, is not affected by the combustion. Generally, even if the polymer is

not present, the observed reduction in height is higher than the reduction in width.

Based on these observations, the value of A_b considered for the estimation of the regression rate is limited to the forward facing ramp surface and the top surface, the two areas more affected by the combustion. Due to the short burning time duration and the relatively small variation of the size observed, to neglect the deformation induced by the paraffin melting at the end of the test, only the initial area is used for the calculation, providing a standard condition for tests comparison. Due to the small variation of cross-section compared to the total port area of the chamber, it can also be initially assumed that the variation of the oxidizer mass flux G_{ox} is negligible during the duration of the combustion tests, therefore a value can be estimated based on the average mass flow rate and initial slab cross-section.

The uncertainties in the estimation of the space and time average regression rate have been calculated following the method described in the ASME standards[44,45]. The method has been specifically translated to the investigation of HRE performances by Frederick and Greiner[36], and applied as in the work of Sanders on slab burners[46]. In the tests analyzed, the burning time estimation proved to be the most important source of uncertainty in the regression rate measurements, especially for long transient times observed in the MOUETTE tests. Longer tests would reduce the effect of the burning time on the regression rate, as well as a faster and more reliable ignition.

The main dataset selected for the analysis of the regression rate of paraffin comes from the fourth test campaign (D), performed at different test conditions, based on different combustion chamber pressure and oxidizer mass flux. When possible, at least three tests at the same conditions have been performed. In order to increase the range of data available, some tests have been selected from the second and third campaign. A summary of the test matrix with the test numbers is given in Table 3 with the pressure expressed as relative pressure, and maintaining the original nomenclature.

While the three tests of the third campaign (C) add more measurements to an already tested value of G_{ox}, the data from the second campaign (B) provide an extended range of analysis. In particular, test B04 has been performed in atmospheric pressure and with a fuel slab with a reduced height, for a low value of G_{ox}. On the opposite side, B08 and B12 present a higher mass flux and combustion chamber pressure, induced by the utilization of a larger chocking orifice. Tests from the first campaign (A) have not been taken into account due to the different slab geometry used.

Generally, as the scattering of the data is an inevitable outcome of experimental research, the access to high-speed camera videos helped in identifying outliers that have a non-nominal behavior and would affect the outcome of the tests. In particular, some of the tests have not been considered in the final discussion, either for detachment of fuel slab from the holder, unsteady combustion or excessively long ignition transient.

The regression rate resulting from the test campaigns is given in Table 4 for the second test campaign, Table 5 for the third and Table 6 for the fourth, along with the experimental data used for the estimation. The regression rate and combustion chamber (relative) pressure are the measured average value of the test, while the G_{ox} is calculated with the average oxidizer mass flow rate divided by the initial port area, as discussed previously. For the same reasoning, A_b is the initial burning area.

Table 3. Matrix of test conditions.

	P_c 0-1 bar	P_c 2-4 bar	P_c 4-6 bar	$P_c \geq 6$ bar
G_{ox} 6-8 kg/m²s	B04, C01, C04, D13-D16	D08-D12	-	-
G_{ox} 10-12 kg/m²s	D02-D04	C09-C10, D01	D05-D07	-
G_{ox} 13-15 kg/m²s	-	-	-	B08-B12

Table 4. Experimental results from the second test campaign.

Test number	Δm_f [g]	t_b [s]	A_b [mm²]	P_c [bar]	G_{ox} [kg/m²s]	$\dot{r}$ [mm/s]
B04	7.62 ± 0.02	3.99 ± 1.26	10963.88 ± 34.01	0.02 ± 0.00	6.61 ± 0.07	0.19 ± 0.06
B08	14.18 ± 0.03	3.51 ± 1.12	10459.30 ± 33.73	9.84 ± 0.98	14.44 ± 0.14	0.39 ± 0.12
B12	20.16 ± 0.10	3.98 ± 1.09	10500.00 ± 200.00	10.96 ± 1.10	13.76 ± 0.14	0.42 ± 0.10

Table 5. Experimental results from the third test campaign.

Test number	Δm_f [g]	t_b [s]	A_b [mm²]	P_c [bar]	G_{ox} [kg/m²s]	$\dot{r}$ [mm/s]
C01	12.53 ± 0.06	4.74 ± 0.84	10442.08 ± 32.95	1.98 ± 0.20	8.24 ± 0.08	0.28 ± 0.05
C02	13.69 ± 0.07	4.44 ± 1.08	10530.00 ± 33.06	2.04 ± 0.20	8.27 ± 0.08	0.32 ± 0.08
C03	9.71 ± 0.05	4.38 ± 1.04	10412.16 ± 32.91	1.92 ± 0.19	7.96 ± 0.08	0.23 ± 0.06
C04	11.89 ± 0.04	5.27 ± 0.66	10232.63 ± 32.78	2.01 ± 0.20	7.54 ± 0.08	0.24 ± 0.06

Table 6. Experimental results from the fourth test campaign.

Test number	Δm_f [g]	t_b [s]	A_b [mm²]	P_c [bar]	G_{ox} [kg/m²s]	$\dot{r}$ [mm/s]
D01	9.99 ± 0.03	4.46 ± 1.54	10566.92 ± 33.25	3.40 ± 0.34	11.57 ± 0.16	0.30 ± 0.14
D03	16.48 ± 0.07	3.75 ± 1.20	9922.70 ± 32.41	0.93 ± 0.09	11.44 ± 0.11	0.48 ± 0.16
D04	14.23 ± 0.07	3.28 ± 1.43	10443.84 ± 33.30	0.90 ± 0.09	11.38 ± 0.11	0.45 ± 0.20
D05	11.54 ± 0.03	3.85 ± 1.57	10450.72 ± 33.29	5.48 ± 0.55	11.36 ± 0.11	0.31 ± 0.13
D06	8.93 ± 0.04	3.91 ± 1.46	10425.23 ± 33.06	4.83 ± 0.48	11.37 ± 0.11	0.24 ± 0.09
D07	11.08 ± 0.04	4.07 ± 1.47	10417.75 ± 33.13	5.17 ± 0.52	11.31 ± 0.11	0.28 ± 0.10
D10	9.59 ± 0.03	4.77 ± 1.99	10638.78 ± 33.44	1.48 ± 0.15	7.62 ± 0.08	0.21 ± v0.09
D11	6.74 ± 0.03	3.02 ± 1.70	10359.90 ± 32.69	1.41 ± 0.14	7.63 ± 0.08	0.23 ± 0.13
D13	9.47 ± 0.04	3.79 ± 0.42	10562.04 ± 33.06	0.34 ± 0.03	7.62 ± 0.08	0.26 ± 0.03
D16	13.67 ± 0.05	4.14 ± 0.43	10465.00 ± 32.95	0.39 ± 0.04	7.54 ± 0.08	0.34 ± 0.04

First and foremost, the loss of mass can be discussed. The initial mass of the slabs is between 210 and 220 grams for all the tests, and only a relatively small loss of mass has been measured experimentally, ranging between 3.8 and 20.2 grams, depending on the burning time of the test. In general, for the type of tests performed with the MOUETTE, a loss of mass never higher than 10% has been measured, and a higher burning time leads to a higher mass consumption, as it is expected. This low quantity of mass consumed during the test translates to a generally small value of the regression rate, with an average of 0.34 mm/s, oscillating between 0.2 and 0.5 mm/s.

The second main observation is based on the analysis of the uncertainties. Based on the methodology adopted, it can be observed that, while the fuel mass loss and the burning area are estimated with good accuracy, the burning time presents large uncertainties. This translates in a large uncertainty in the calculated regression rate, and the quality of the data needs to be assessed critically before investigating the effect on regression of G_{ox} and P_c.

With the considerations given, the regression rate over mass flux plot can now be introduced, shown in Figure 7. In the graph, the Marxman's law fitting have been plotted for all the data, for the pressurized tests only and for the atmospheric tests only.

By observing the plotted data, some trends can be deducted. First, different clouds of data can be identified, which are distinguished by the value of G_{ox}. The uncertainty bars on the G_{ox} have been omitted, for clarity of presentation, as the uncertainty is on average of 1%.

The first conclusion that can be drawn from these results concerns the effect of the mass flux on the regression rate. Observing both the results obtained at atmospheric pressure, and the results obtained at pressurized conditions, a dependency between the measured regression rate and the oxidizer mass flux appears, further confirmed by the results of the higher G_{ox} tests, B08 and B12, and the lower G_{ox} test, B04. The results fit with the model developed by Marxman for the dependency of

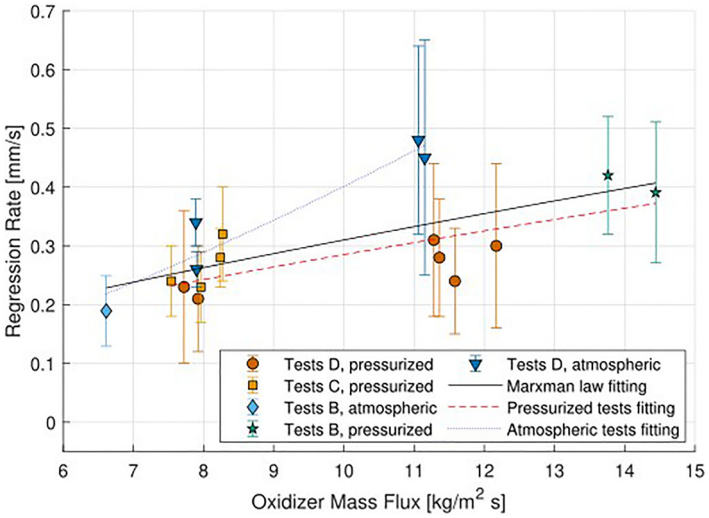

Figure 7. Regression rate against oxidizer mass flux.

the average regression rate over the oxidizer mass flux. Ideally, the trend should be further investigated with the addition of more experimental points, to increase the range of G_{ox} conditions tested.

In particular, the high and low G_{ox} points have been determined with a limited number of tests, and more repeatable tests should be performed in these conditions to increase the reliability of the prevision, and to confirm the results of B04, B08 and B12.

The second conclusion concerns the effect of pressure. To assess the influence of pressure on the combustion, different tests have been performed at the same G_{ox} condition, but adjusting the nozzle throat to have a larger spectrum of analysis.

Even though the results have been acquired in different pressure levels, they all seem to group around a common center, dictated mainly by the mass flux. These results suggest a minimal impact of pressure on the regression rate, which is expected from theory[47].

An outlier from the trend is given by the atmospheric pressure tests. Excluding B04, that can't be compared with other tests performed at the same G_{ox} conditions, they all present a higher measured regression rate. While satisfying the conditions of higher oxidizer mass flux equal higher regression rate, they all present a higher measured value than the one taken from pressurized tests. It has been observed that the slabs burned at higher pressure conditions present lower dimensions after the tests, suggesting that a higher consumption of the fuel is present. However, this also comes at the cost of a larger amount of melted paraffin deposits in the combustion chamber, suggesting that part of the heat absorbed by the slab surface melts the fuel, but might be not enough to pyrolyze it and burn.

A possible cause for the increased regression rate should be identified in the test procedure, and in particular on the transitory shut-off of the MOUETTE. At the end of the test a flow of nitrogen is fed in the combustion chamber, halting the combustion and cooling down the slab surface. The flow of nitrogen on the paraffin slab, which presents a melted liquid layer, could lead to the break-up of droplets from the surface, their entrainment in the nitrogen flow and expulsion from the nozzle, which has a larger throat area for the atmospheric tests. The effect of purge could increase the measured regression rate, as the mass of ejected paraffin droplets should have a relatively higher impact on the total measured mass loss, and its impact should be assessed by performing tests with without purging, letting the paraffin cool down in the chamber.

The variation of regression rate as a function of oxidizer mass flux has been fitted with a power law, based on the Marxman's diffusion-limited model:

$$\dot{r} = a_0 G_{ox}^n$$

In particular, three fittings have been calculated, as plotted in Figure 7: one for atmospheric tests, one for pressurized tests, and a general one with all the data available. The resulting coefficients are listed in Table 7.

To evaluate the results, a comparison with experimental data listed in literature is required. The values available have been listed in Table 8. Unfortunately, limited fitting laws with a slab burner are available in literature, and only the curves of Nakagawa *et al.*[11] and Dunn *et al.*[23] are reported. They both report an average regression rate between the tests around 0.35 mm/s. Petrarolo[48] and Kobald *et al.*[49] both perform also tests with gaseous oxidizer and paraffin in a slab burner in

Table 7. Regression rate parameter results.

Test number	a_0	n	R^2	P_c	G_{ox}
Atmospheric tests	0.014	1.471	0.92	0.5 bar	5-11 kg/m²s
Pressurized tests	0.054	0.726	0.59	2.5-10 bar	7.5-14.5 kg/m²s
All tests	0.057	0.739	0.42	0.5-10 bar	5-14.5 kg/m²s

Table 8. Regression rate parameters from literature.

Reference	Oxidizer	Fuel	a_0	n	R^2	P_c	G_{ox}
Nakagawa *et al.*[11]	GOX	Paraffin	0.069	0.595	[-]	atmospheric	10-30 kg/m²s
Dunn *et al.*[23]	GOX	Paraffin	0.079	0.544	[-]	atmospheric	5.2-16.2 kg/m²s
Karabeyoglu *et al.*[50]	GOX	Paraffin	0.117	0.620	[-]	0.1-5.9	16-369 kg/m²s
Quadros *et al.*[51]	GOX	Paraffin	0.496	0.620	[-]	atmospheric	15-32 kg/m²s
Karabeyoglu *et al.*[52]	GOX	Paraffin	0.082	0.718	0.97	[-]	[-]
Narsai[53]	GOX	Paraffin	0.114	0.644	0.64	[-]	[-]
Karabeyoglu *et al.*[50]	GOX	Paraffin	0.144	0.590	0.70	[-]	[-]
Di Martino *et al.*[54]	GOX	Paraffin	0.103	0.712	0.84	[-]	[-]
Evans *et al.*[55]	GOX	Paraffin	0.672	0.600	[-]	[-]	63-123 kg/m²s
Karabeyoglu *et al.*[56]	GOX	Paraffin	0.427	0.735	[-]	atmospheric	43-119 kg/m²s

a similar range of G_{ox}, obtaining a regression rate between 0.2 and 0.6 mm/s, but don't disclose the a_0 and n coefficient values. The other data presented have been evaluated for a conventional combustion chamber, with a cylindrical fuel grain. Moreover, when specified, the range of G_{ox} is generally higher then what tested in the MOUETTE.

A graphical description is also given in Figure 8, plotting the curves available in literature alongside the MOUETTE data, in the region of interest. The pressure has been converted to relative pressure for comparison.

The value of n evaluated from the pressurized tests, equal to 0.726, is in the range of the experimental observations found in literature, ranging typically between 0.6 and 0.8. The value obtained for the atmospheric tests is much higher, of 1.471, and such a high value suggests that the limitations in the regression rate estimation method have to be taken into account.

The value of a_0, on the other hand, is lower than literature, but this could be justified by the limited range of G_{ox} used for the investigation, plus the large scattering, shown by the low value of the parameter R-squared. If compared with the results of Nakagawa *et al.* and Dunn *et al.*, performed in a slab burner, the order of magnitude is similar.

The overall fitting lies at the limit of the experimental range reported in literature, but is influenced by the scattering induced by the atmospheric tests, and qualitatively follows the trend given by other researchers shown in Figure 8.

Generally, for a more reliable prediction, a larger amount of points should be tested, especially by changing the value of the oxidizer mass flux, to increase the data interval for the fit.

Internal ballistics visualization

The main purpose of MOUETTE test bench is the acquisition of high-speed videos of the fuel combustion.

In general, the videos have been analyzed to provide more insight on the combustion process, and a first detailed view of combustion of paraffin on the surface of the fuel slab is shown in Figure 9. This figure is a magnification of a frame taken from test B04, and is used to give an example of what is observed in every test. The frame has been recorded at 2000 fps, with a lens aperture of f/8, a shutter speed of 1/593000 s and a resolution 896x512 pixels.

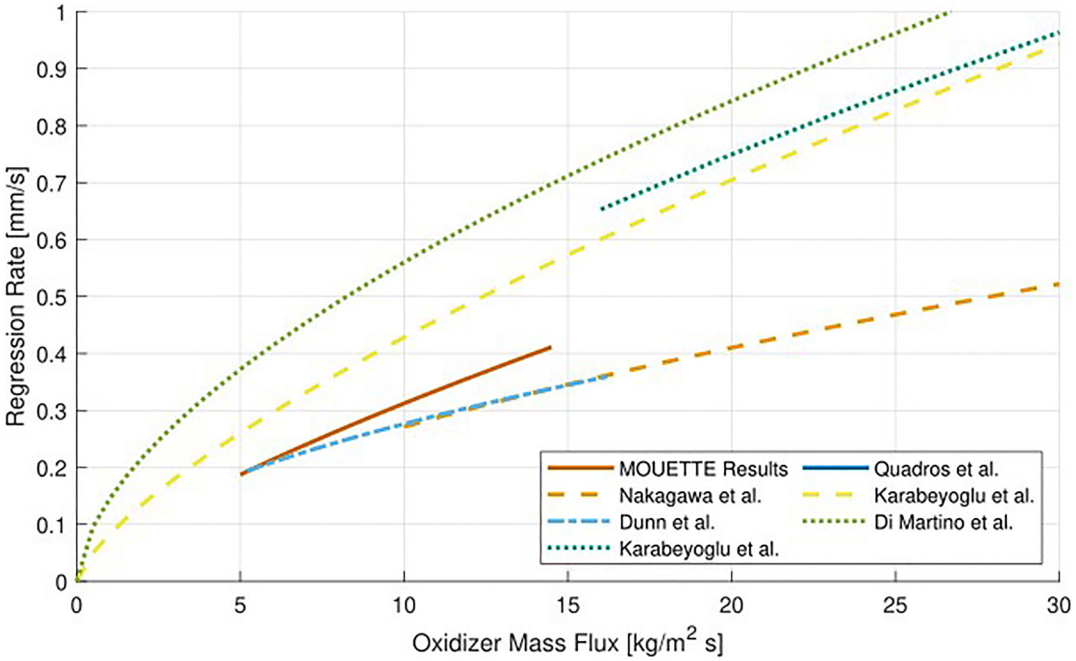

Figure 8. Regression rate against oxidizer mass flux from literature.

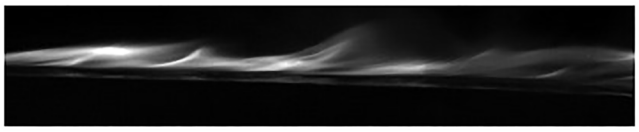

Figure 9. Diffusion flame visualized in test B04, oxidizer flowing from left to right.

Looking at the figure, the black area on the bottom is the lateral surface of the fuel slab. On top of it there is a narrow bright thin line, before a second dark area. The bright zone is assumed to be the liquefied surface of the paraffin slab, which glows reflecting the light of the flame. Between the liquid surface and the flame core there is the fuel rich dark zone, which is filled by the mass flux of gaseous pyrolyzed fuel coming from the slab surface. Over the flame zone there is a second dark area, which is oxidizer rich and filled by the oxygen mass flow. This diffusive flame structure observed experimentally is in accordance with the theoretical models described in literature of the hybrid rocket combustion in the boundary layer.

To investigate the effect of the gaseous oxidizer mass flux and chamber pressure on the flame, the tests have been categorized based on the tested conditions. The operative points are four, summarized in Table 9, all taken from the fourth test campaign. Tests D08 and D09, performed at the same conditions of test D10, have been excluded from the regression rate analysis due to the excessively long ignition transient compared to the burning time, due to problems in the igniter composition, but the steady state videos can be included for a qualitative description of the combustion behavior.

Table 9. Matrix of test conditions.

Low pressure Low mass flux	Low pressure High mass flux
D13, D16	D03, D04
High pressure Low mass flux	High pressure High mass flux
D08, D09, D10	D01, D05, D06, D07

Some frames taken from the four tests conditions are presented in Figures from Figure 10 to Figure 13. These frames have been acquired with the same camera settings and allow for a direct comparison. The frames have been recorded at 2000 fps, with a lens aperture of f/16, a shutter speed of 1/593000 s and a resolution 896x512 pixels.

The effect of the mass flux and of pressure on the combustion can be observed qualitatively. First, an increase in G_{ox} at the same pressure conditions is acting on the heat exchange at the

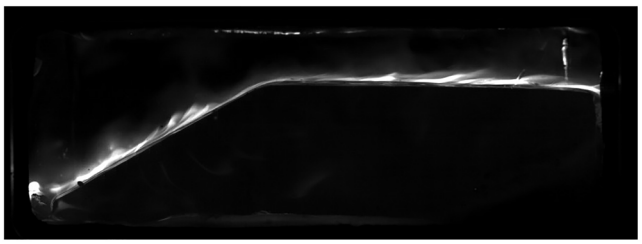

Figure 10. Test D13.

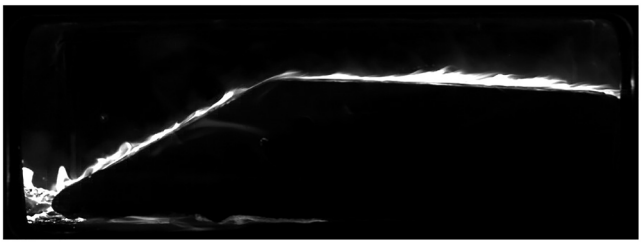

Figure 11. Test D04.

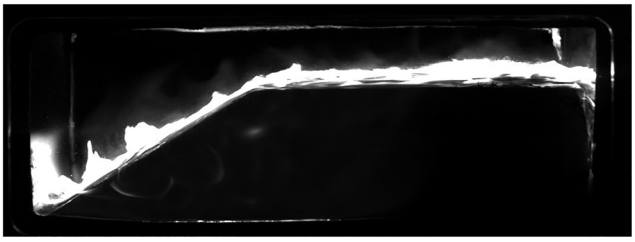

Figure 12. Test D08.

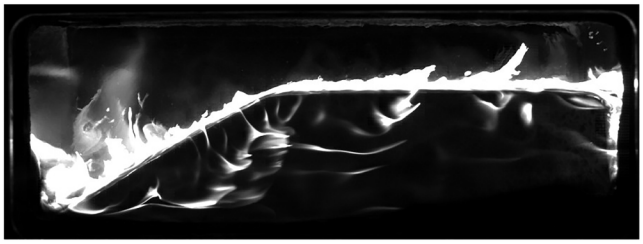

Figure 13. Test D06.

surface as predicted by the diffusion-limited model and generating a higher regression rate, which is shown by the more intense emission of soot in the visible light spectrum. An increase in the mass flux, while translating in a higher regression rate, should also decrease the flame thickness[26] and this will be assessed in the future through image analysis techniques, taking into account the insurgence of blowing events induced by droplets break-up and combustion instabilities.

The effect of pressure, on the other hand, couldn't be assessed from the space and time average regression rate data, but it's visible using the high-speed camera. In particular, higher pressure translates in again a thicker saturated area of the flame, and in combination with a higher G_{ox} this brings to the more energetic conditions, with flames developing also on the sides of the slab, and more frequent and intermittent blowing events from the fuel surface. Moreover, the effect of the recirculation zone at the beginning of the forward-facing ramp, is even more visible.

In general, a wider spectrum of combustion chamber pressure at low G_{ox} should be investigated, to quantify if an effect is present on the regression rate.

Concerning the entrainment of liquid fuel droplets in the oxidizer flow, the small droplets typically can't be visualized in the videos gathered. The reasons could be multiple. First, the droplet size could be too small to be captured by the camera. Second, the brightness of the flame saturates the image in proximity of the droplets, which are burning cores themselves, therefore enveloped by a burning surface. Larger liquid droplets can be however visualized in correspondence with local blowing events at the surface of the grain, typically coupled with pressure increases induced by the enhanced instantaneous fuel mass flow. A photograph, taken from test B08, is shown in Figure 14, where the burning fuel droplets ejected in the oxidizer flow by some local surface instabilities can be identified.

An interesting result towards the droplets ejection mechanism at the liquid surface layer of investigation comes from test B15. Test B15 has been performed with a G_{ox} in the range of 12 kg/m^{2}s, with a relative combustion chamber pressure of around 0.5 bar, slightly reduced by the presence of a small leak on one of the windows, induced by the ignition wires being stuck between the window gasket and the combustion chamber. The wires burn and illuminate the fuel grain surface, shedding light to the Kelvin-Helmholtz instability phenomena, in which the unstable liquid layer developing on the fuel surface forms roll waves which break-up and release liquid droplets, entrained in the flow.

The phenomenon is shown in a sequence of frames taken from the acquired high-speed video, at an interval of 0.5 ms between each frame. The photographs from Figure 15 to Figure 22 show 3.5 ms of a droplet release event. In the pictures, the oxidizer is flowing from left to right, and only the upper

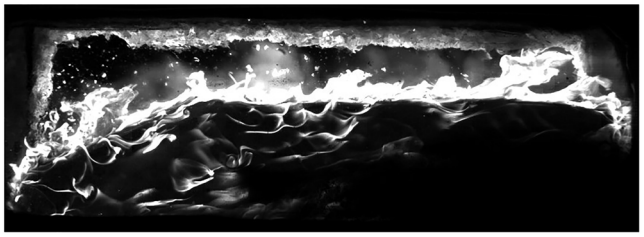

Figure 14. Droplets combustion events observed in test B08.



Figure 15. Droplets release observed in test B15. Time = t0.



Figure 16. Droplets release observed in test B15. Time = t0 + 0.5 ms.



Figure 17. Droplets release observed in test B15. Time = t0 + 1 ms.



Figure 18. Droplets release observed in test B15. Time = t0 + 1.5 ms.



Figure 19. Droplets release observed in test B15. Time = t0 + 2 ms.



Figure 20. Droplets release observed in test B15. Time = t0 + 2.5 ms.



Figure 21. Droplets release observed in test B15. Time = t0 + 3 ms.



Figure 22. Droplets release observed in test B15. Time = t0 + 3.5 ms.

surface of the slab is shown. The frames have not been adjusted in brightness or contrast.

At first, small liquid protrusions develop on the fuel surface, which start to grow in size and height. Once the waves reach a critical height, they break up and release small droplets in the flow, which evaporates and burn in the flame zone. It can also be noticed that, as the wave fronts grow in height and become more unstable, the background becomes brighter, and the flame fronts develops, suggesting that small paraffin droplets are being entrained in the oxidizer flow and burn. These images show the direct release mechanism of paraffin droplets in a reacting flow, a result hardly achieved in literature, and with a good resolution, that will be used in future works for the calculation of number of droplets, diameter and distribution. This result is a first starting point for the definition of targeted tests in order to visualize the droplet entrainment phenomena at the different chamber conditions.

Conclusions

A hybrid rocket slab burner has been used to investigate the combustion of paraffin, one of the most interesting fuels for HREs due to its high regression rate induced by the liquefying properties.

As outcome of the tests discussed in this article, some features of paraffin combustion have been observed and measured. First, the effect of the oxidizer mass flux on the regression rate has been assessed, and the results are in accordance with the predictions coming from literature, as an increase in mass flux leads to an increase in regression rate. The effect of pressure, on the other hand, seems to be inconclusive, probably due to the limited range of combustion chamber pressures tested, and further investigations are required. Moreover, due to the short burning time, the uncertainties on the results are relatively high, and tests with longer steady-state phases should be performed in the future to address this issue.

In general, to deeply understand the behavior of paraffin combustion and to verify the existing models of the combustion process, a larger amount of tests need to be performed, in particular on a larger oxidizer mass flux range.

The developed test bench and the preliminary results suggest different lines of research to follow. First, a set of non-liquefying fuels tests should be performed, in order to provide a reference that can be used to assess the effect of the unstable liquid layer and droplets entrainment in the increase in regression rate of paraffin fuels. Then, a larger database of paraffin combustion in different operative conditions should be created through more experimental testing, to improve the predictions given in this work.

Ethics and consent

Ethical approval and consent were not required.

Data availability

The experimental data of the three test campaigns analyzed in this article are available on the Zenodo repository:

Gelain, R. (2025). MOUETTE Test Data - Second Test Campaign (B) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.16992234

Gelain, R. (2025). MOUETTE Test Data - Third Test Campaign (C) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.16992272

Gelain, R. (2025). MOUETTE Test Data - Fourth Test Campaign (D) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.16992313

The datasets are licensed under a Creative Commons Attribution 4.0 International License (CC-BY 4.0), allowing for reuse and adaptation with proper attribution.

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References

1. Altman D, Holzman A: **Overview and history of hybrid rocket propulsion.** *Fundamentals of Hybrid Rocket Combustion and Propulsion.* Edited by MJ Chiaverini, and KK Kuo. Progress in Astronautics and Aeronautics, AIAA, Reston, VA, 2007; **218**.
Publisher Full Text
2. Glaser C, Hijlkema J, Anthoine J: **Bridging the technology gap: strategies for hybrid rocket engines.** *Aerospace.* 2023; **10**(10): 901.
Publisher Full Text
3. Okninski A: **On use of hybrid rocket propulsion for suborbital vehicles.** *Acta Astronaut.* 2018; **145**(part 1): 1–10.
Publisher Full Text
4. Fry R, DeLuca L, Gadio G, *et al.*: **Solid propellant burning rate measurement methods used within the NATO propulsion community.** In: *37th Joint Propulsion Conference and Exhibit*. 2001; AIAA, 3948.
Publisher Full Text
5. DeLuca LT, Galfetti L, Colombo G, *et al.*: **Time-resolved burning of solid fuels for hybrid rocket propulsion.** *Progress in Propulsion Physics.* 2011; **2**: 405–426.
Publisher Full Text
6. Strand L, Ray R, Cohen N: **Hybrid rocket combustion study.** In: *29th Joint Propulsion Conference and Exhibit*. 1993; 2412.
Publisher Full Text
7. Leccese G, Cavallini E, Pizzarelli M: **State of art and current challenges of the paraffin-based hybrid rocket technology.** In: *AIAA propulsion and energy 2019 forum*. 2019; 4010.
Publisher Full Text
8. Cantwell B, Karabeyoglu A, Altman D: **Recent advances in hybrid propulsion.** *International Journal of Energetic Materials and Chemical Propulsion.* 2010; **9**(4): 305–326.
Publisher Full Text
9. Veale K, Adali S, Pitot J, *et al.*: **A review of the performance and structural considerations of paraffin wax hybrid rocket fuels with additives.** *Acta Astronaut.* 2017; **141**: 196–208.
Publisher Full Text
10. Kim S, Lee J, Moon H, *et al.*: **Effect of paraffin-LDPE blended fuel on the hybrid rocket motor.** In: *46th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*. 2010; 7031.
Publisher Full Text
11. Nakagawa I, Hikone S: **Study on the regression rate of paraffin-based hybrid rocket fuels.** *J Propuls Power.* 2011; **27**(6): 1276–1279.
Publisher Full Text
12. Chandler A, Jens E, Cantwell B, *et al.*: **Visualization of the liquid layer combustion of paraffin fuel for hybrid rocket applications.** In: *48th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*. 2012; 3961.
Publisher Full Text
13. Jens ET, Miller VA, Cantwell BJ: **Schlieren and OH* chemiluminescence imaging of combustion in a turbulent boundary layer over a solid fuel.** *Exp Fluids.* 2016; **57**(3): 39.
Publisher Full Text
14. Jens ET, Karp AC, Miller VA, *et al.*: **Experimental visualization of hybrid combustion: results at elevated pressures.** *J Propuls Power.* 2020; **36**(1): 33–46.
Publisher Full Text
15. Kobald M, Ciezki H, Schlechtriem S: **Optical investigation of the combustion process in paraffin-based hybrid rocket fuels.** In: *49th AIAA/ASME/SAE/ASEE Joint Propulsion Conference.* 2013; 3894.
Publisher Full Text
16. Kobald M, Petrarolo A, Schlechtriem S: **Combustion visualization and characterization of liquefying hybrid rocket fuels.** In: *51st AIAA/SAE/ASEE Joint Propulsion Conference*. 2015.
Publisher Full Text
17. Petrarolo A, Kobald M, Schlechtriem S: **Liquid layer combustion visualization of paraffin-based hybrid rocket fuels.** In: *53rd AIAA/SAE/ASEE Joint Propulsion Conference*. 2017; 4828.
Publisher Full Text
18. Petrarolo A, Kobald M, Schlechtriem S: **Understanding Kelvin–Helmholtz instability in paraffin-based hybrid rocket fuels.** *Exp Fluids.* 2018; **59**(4): 62.
Publisher Full Text
19. Petrarolo A, Kobald M, Schlechtriem S: **Visualization of combustion phenomena in paraffin-based hybrid rocket fuels at super-critical pressures.** In: *2018 Joint Propulsion Conference*. 2018; 4927.
Publisher Full Text
20. Wada Y, Kawabata Y, Kato R, *et al.*: **Observation of combustion behavior of low melting temperature fuel for a hybrid rocket using double slab motor.** *International Journal of Energetic Materials and Chemical Propulsion.* 2016; **15**(5): 351–369.
Publisher Full Text
21. Paravan C, Bisin R, Carlotti S, *et al.*: **Diagnostics for entrainment characterization in liquefying fuel formulations.** In: *2018 Joint Propulsion Conference*. 2018; 4663.
Publisher Full Text
22. De Morais Bertoldi AE, Bouziane M, Hendrick P, *et al.*: **Development and test of magnesium-based additive for hybrid rockets fuels.** In: *2018 SpaceOps Conference*. 2018; 2383.
Publisher Full Text
23. Dunn C, Gustafson G, Edwards J, *et al.*: **Spatially and temporally resolved regression rate measurements for the combustion of paraffin wax for hybrid rocket motor applications.** *Aerosp Sci Technol.* 2018; **72**: 371–379.
Publisher Full Text
24. Ozawa K, Yoshino T, Tsuboi N: **Visualization of boundary layer combustion of wax fuels in vertical and horizontal configurations.** In: *2018 Joint Propulsion Conference*. 2018; 4928.
Publisher Full Text
25. Budzinski K, Aphale SS, Ismael EK, *et al.*: **Radiation heat transfer in ablating boundary layer combustion theory used for hybrid rocket motor analysis.** *Combust Flame.* 2020; **217**: 248–261.
Publisher Full Text

26. Liu LL, Zhang TY, Chen ZB, *et al.*: **Boundary layer combustion of paraffin fuels for hybrid propulsion applications.** *Acta Astronaut.* 2022; **193**: 338–345.
Publisher Full Text

27. Gelain R: **Experimental Investigation of paraffin combustion in a hybrid rocket slab burner.** 2024.

28. Gelain R, Angeloni F, Bertoldi ADM, *et al.*: **Design and commissioning of the MOUETTE hybrid rocket slab burner.** In: *9th European Conference for Aeronautics and Space Sciences (EUCASS).* July, 2022.
Publisher Full Text

29. DeLuca LT, Galfetti L: **Burning of metallized composite solid rocket propellants: from micrometric to nanometric aluminum size.** In: *Proceedings of the Korean Society of Propulsion Engineers Conference.* The Korean Society of Propulsion Engineers, 2008; 886–898.
Reference Source

30. Lee J, Ko S, Kim S, *et al.*: **Mass transfer due to liquid film of paraffin-based fuels for hybrid rocket engines.** *Aerosp Eur Conf.* 2023.
Publisher Full Text

31. Ishigaki T, Nakagawa I: **Improving physical properties of wax-based fuels and its effect on regression rate.** *J Propuls Power.* 2020; **36**(1): 123–128.
Publisher Full Text

32. Barato F, Grosse M, Bettella A: **Hybrid rocket fuel residuals-an overlooked topic.** In: *50th AIAA/ASME/SAE/ASEE Joint Propulsion Conference*. 2014; 3753.
Publisher Full Text

33. Faenza M, Boiron A, Karp A, *et al.*: **HRTC regression rate standards**. 2020.
Reference Source

34. DeLuca LT, Annovazzi A: **Survey of burning rate measurements in small solid rocket motors.** *FirePhysChem.* 2024; **4**(2): 146–165.
Publisher Full Text

35. Karp AC, Jens ET: **Hybrid rocket propulsion design handbook**. Academic Press, 2023.
Reference Source

36. Frederick Jr RA, Greiner BE: **Laboratory-scale hybrid rocket motor uncertainty analysis.** *J Propuls Power.* 1996; **12**(3): 605–611.
Publisher Full Text

37. Paravan C, Galfetti L, Bisin R, *et al.*: **Combustion processes in hybrid rockets.** *International Journal of Energetic Materials and Chemical Propulsion.* 2019; **18**(3): 255–286.
Publisher Full Text

38. Kang S, Lee D, Lee E, *et al.*: **Design and performance evaluation of hybrid rocket using 95 wt.% H2O2.** In: *52nd AIAA/SAE/ASEE Joint Propulsion Conference.* 2016; 4864.
Publisher Full Text

39. Carmicino C, Russo Sorge A: **Experimental investigation into the effect of solid-fuel additives on hybrid rocket performance.** *J Propuls Power.* 2015; **31**(2): 699–713.
Publisher Full Text

40. Zilliac G, Karabeyoglu M: **Hybrid rocket fuel regression rate data and modeling.** In: *42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit.* 2006; 4504.
Publisher Full Text

41. Glaser C, Gelain R, Bertoldi AEM, *et al.*: **Experimental regression rate profiles of stepped fuel grains in Hybrid Rocket Engines.** *Acta Astronautica.* 2023; **204**: 186–198.
Publisher Full Text

42. Glaser C, Hijlkema J, Lestrade JY, *et al.*: **Influences of steps in hybrid rocket engines: simulation and validation on simplified geometries.** *Acta Astronaut.* 2023; **208**: 1–14.
Publisher Full Text

43. Salama A: **Velocity profile representation for fully developed turbulent flows in pipes: a modified power law.** *Fluids.* 2021; **6**(10): 369.
Publisher Full Text

44. Abernethy RB, Benedict RP, Dowdell RB: **ASME measurement uncertainty.** J *Fluids Eng.* 1985; **107**(2): 161–164.
Publisher Full Text

45. Dieck RH: **Measurement uncertainty models.** *ISA Trans.* 1997; **36**(1): 29–35.
Publisher Full Text

46. Sanders IC: **Hybrid combustion Analysis Via Laser Absorption Spectroscopy for Rocket Propulsion and Fire Environments.** University of California, Los Angeles, 2023.
Reference Source

47. Marxman GA, Wooldridge CE, Muzzy RJ: **Fundamentals of hybrid boundary-layer combustion.** In: *Progress in astronautics and rocketry.* Elsevier, 1964; **15**: 485–522.
Publisher Full Text

48. Petrarolo A: **Liquid layer combustion instabilities in paraffin-based hybrid rocket fuels.** Doctoral dissertation, Universität Stuttgart, 2020.
Reference Source

49. Kobald M, Toson E, Ciezki H, *et al.*: **Rheological, optical, and ballistic investigations of paraffin-based fuels for hybrid rocket propulsion using a two-dimensional slab-burner.** *Progress in Propulsion Physics.* 2016; **8**: 263–282.
Publisher Full Text

50. Karabeyoglu A, Zilliac G, Cantwell BJ, *et al.*: **Scale-up tests of high regression rate paraffin-based hybrid rocket fuels.** *J Propuls Power.* 2004; **20**(6): 1037–1045.
Publisher Full Text

51. Quadros FDA, Lacava PT: **Swirl injection of gaseous oxygen in a lab-scale paraffin hybrid rocket motor.** *J Propuls Power.* 2019; **35**(5): 896–905.
Publisher Full Text

52. Karabeyoglu M, Cantwell B, Altman D: **Development and testing of paraffin-based hybrid rocket fuels.** In: *37th joint propulsion conference and exhibit.* 2001; 4503.
Publisher Full Text

53. Narsai P: **Nozzle erosion in hybrid rocket motors.** Doctoral dissertation, Stanford University, 2016.
Reference Source

54. Di Martino GD, Mungiguerra S, Carmicino C, *et al.*: **Two-hundred-newton laboratory-scale hybrid rocket testing for paraffin fuel-performance characterization.** *J Propuls Power.* 2019; **35**(1): 224–235.
Publisher Full Text

55. Evans B, Favorito N, Kuo K: **Study of solid fuel burning-rate enhancement behavior in an X-ray translucent hybrid rocket motor.** In: *41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*. 2005; 3909.
Publisher Full Text

56. Karabeyoglu A, Cantwell B, Stevens J: **Evaluation of the homologous series of normal alkanes as hybrid rocket fuels.** In: *41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit.* 2005; 3908.
Publisher Full Text

Open Peer Review

Current Peer Review Status: ✗ ? ? ?

Version 1

Reviewer Report 30 March 2026

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Kolos Retfalvi
University at Buffalo, Buffalo, NY, USA
Elektra Ismael Katz
University at Buffalo Department of Mechanical and Aerospace Engineering, Buffalo, New York, USA

The paper titled, "Investigation of Paraffin Combustion in a Hybrid Rocket Slab Burner," details an investigation of the MOUETTE paraffin wax slab burner setup. The paper presents results from four experimental campaigns conducted under varying operating conditions. The fuel used is low carbon weight-percent paraffin wax, and the oxidizer is GOx. The observed performance characteristics across multiple tests appear to correlate well with published results. The study first draws qualitative conclusions regarding flame shape and boundary layer height under varying mass fluxes and chamber pressures. Finally, the paper discusses qualitative observations of a single droplet ejection mechanism. Overall, the paper is well written but due to the lack of quantitative analysis, it needs a major revision.

Major Recommendations:
The authors are encouraged to include a clear novelty statement in the paper and to provide a more quantitative analysis of the quantities of interest in the slab burner experiments. While the experimental work is presented very well, there is a lack of analysis for the manuscript to be considered a strong academic contribution. The primary research objective in current slab burner experiments is to investigate liquid film behavior for atomization studies. The authors are strongly encouraged to examine more recent work by (refer to 1,2,3,4) , who have measured droplet size distributions, visualized bag, ligament, and catastrophic breakup mechanisms, normalized droplet distributions using z-scores, and performed related quantitative analyses. Most of these recommended papers record paraffin droplets under heated air environments, and none in combustion environments. The novelty of this work can include some of the previously mentioned methods for analyzing droplet statistics and wave analysis, but applied in a combustion environment. Recent film analyses have been applied for both heated air and combustion environments, but is still not fully studied for hybrid motors. Alternatively, it is recommended that the authors further explore literature from the nuclear engineering field regarding mass

entrainment, as boiling is often cited as a source of entrainment and boiling effects are frequently underrepresented in current hybrid rocket literature.

Minor Formatting Issues:
Figures 10-13 require improved labeling to clearly indicate the operating conditions (e.g., low G, low p, etc.) that are currently mentioned only in the captions.
Figures 15-18 are overall useful, however, annotating the droplet trajectory on the figures would be helpful, and possibly combining them into a single figure could improve clarity.
Double-check the grammar and proofread the study for minor spelling errors.

References

1. Katz Ismael E, Budzinski K, DesJardin P: Droplet entrainment and size distributions from flow separation over a melting paraffin slab. *Experiments in Fluids*. 2025; **66** (9). Publisher Full Text
2. Lee J, Ko S, Park T, Moon H: Influence of liquid film on fuel consumption behavior in paraffin-based hybrid rocket engines at low mass flux. *Aerospace Science and Technology*. 2026; **168**. Publisher Full Text
3. Liu X, Hu S, Wang Y, Zhang W, et al.: Droplet entrainment characteristics of HTPB/Paraffin blended fuels for hybrid rocket motors. *Acta Astronautica*. 2024; **214**: 293-302 Publisher Full Text
4. 10.2514/6.2018-4663.

Is the work clearly and accurately presented and does it cite the current literature?
Partly

Is the study design appropriate and does the work have academic merit?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?
Yes

If applicable, is the statistical analysis and its interpretation appropriate?
Partly

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Computational combustion and reacting flows, Slab burner experiments

We confirm that we have read this submission and believe that we have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however we have significant reservations, as outlined above.

Reviewer Report 24 February 2026

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Sergio Cassese
University of Naples Federico II, Naples, Italy

The work addresses the characterization of paraffin, a fuel widely used in hybrid rocket applications. In particular, the authors derive a regression law for the simplified case of a paraffin slab burner and subsequently present several frames of the combustion process obtained through the use of optical access to the combustion chamber. The paper is generally well written and does not present grammatical or typographical errors; however, there are several critical issues that should be taken into consideration in order to improve the overall quality of the manuscript.
There are essentially four very important aspects that I would like to highlight to the authors and that require careful evaluation:

- From the text, it is not clear what novelty this work brings to the scientific community. Studies on paraffin characterization, including more advanced configurations, are already available in the literature, as is well known to the authors. Therefore, the authors are asked to clearly highlight which aspects, in their view, allow this work to fill a gap with respect to the existing literature.
- The characterization of the regression rate as a function of mass flux and pressure does not represent an absolute novelty, but it may still be of interest given the configuration investigated by the authors. However, the data-processing methodology, which results in very large error bars, makes the observed trends not particularly reliable, with uncertainties reaching up to ±50%. Beyond the data dispersion justified by the authors, I recommend reconsidering the data-processing approach in order to reduce, at least, the error propagation in the performed tests.
- As stated several times in the manuscript, the characterization would require additional tests, since from several perspectives (both mass flux and pressure effects), the available dataset is rather limited.
- The entire discussion related to the combustion chamber videos lacks quantitative results and is based solely on a series of images that qualitatively show phenomena that are generally already well known. The authors state that this is a preliminary analysis intended to support future developments, including quantitative analyses related to entrainment phenomena. However, as presented, this further weakens the robustness of the reported results.

Below I list a series of detailed comments related to the manuscript, many of which overlap with the points mentioned above:

- The authors are encouraged to mention some of the quantitative results already in the abstract, in order to make it clearer to the reader what was actually achieved in the study.
- In the introduction, it is stated that hybrid rockets use liquid oxidizers. I suggest also mentioning gaseous oxidizers, especially since in research applications most hybrid rockets

employ gaseous oxidizers, as is also the case in the present work.

- Still in the introduction, several literature works related to this topic are listed, but the gaps in the existing literature are not clearly identified. The authors should explicitly state what novelty they intend to introduce, after having reviewed the existing studies.
- The experimental apparatus is not described in sufficient detail. Rather than including it in the methodology section, I suggest creating a dedicated paragraph or chapter on the experimental setup, where the motor configuration used in this work is clearly explained, possibly including a cross-section with all components and dimensions to facilitate reader understanding.
- In relation to the previous point, in addition to the motor, I would also include in the same chapter a schematic of the feed system, highlighting the sensors used, their location, manufacturer, and datasheet uncertainties. This would improve both reproducibility and clarity.
- The use of a 0.5% black pigment should be justified. Do the authors have a specific motivation or a quantitative estimate of its effect on radiation? Why was this specific percentage chosen? Please clarify.
- On page 5, a space is missing in “30mm”.
- In addition to the sensors used in the feed line, the sensors installed on the motor itself should also be indicated, including their precise locations.
- The value of the discharge coefficient Cd equal to 0.6 is stated as being “derived.” Is there a bibliographic reference for this value, or was it obtained within the present work? A quantitative justification would improve completeness.
- In the results section, it is stated that the central part of the slab is more consumed. Why does this occur? How is the oxidizer injected? The authors should clearly explain whether the injection is uniform or concentrated in the central region, which would justify the observed burning pattern.
- When defining how the regression rate is estimated, the authors discuss the method used for cylindrical ports. This digression does not add value to the work and should be removed, as it only lengthens the discussion and distracts from the paper’s objectives.
- The explanation of how the regression rate is calculated belongs to the methodology section rather than the results section. I therefore suggest moving this entire part accordingly.
- The authors state that Type-A tests are not used in the results. For this reason, I believe they should be completely removed and not mentioned, as they do not provide any useful information. The experimental campaigns and tests should be renamed considering only those actually used for data processing and results. The same applies to any other tests that were ultimately excluded.
- In the summary tables of the tests, I suggest also including the oxidizer mass flow rate for completeness.
- With reference to Figure 7, the authors should clearly explain how the error bars were obtained and how the uncertainty-propagation analysis was performed, possibly by adding a dedicated paragraph in the methodology section.
- Some obvious statements, such as the fact that longer burning times increase mass consumption or that the results are in agreement with theory, could be removed. These comments are self-evident and do not add significant value.
- I recommend revisiting the trends shown in Figure 7. Looking at the pressurized test data points, the trend appears to show a positive curvature, since tests performed at mass fluxes between 11 and 12 kg/m^{2}s lie significantly below the expected values. I may be mistaken,

but with a power-law fit, a positive curvature would be expected. Please re-evaluate these trends.
- The cause of the high regression rate observed in atmospheric tests remains an open issue, and the proposed explanation is unfortunately not solid, as it has not been experimentally verified. Nevertheless, I appreciate the authors' effort to provide a possible justification. If they are able to confirm their hypothesis experimentally, this would be very interesting.
- When it is stated that tests at different pressures provide similar results, which specific data points are being referred to? Although the comment is generally understandable, the reader cannot immediately visualize this and must manually identify the corresponding tests. I suggest explicitly stating which tests are being discussed.
- On page 12, a figure is mentioned without being cited. I recommend always including proper cross-references.
- As anticipated, the entire section related to the videos is unfortunately purely qualitative and does not provide much novelty in its current form. Some parts describe well-known phenomena, such as the classical diffusion flame. The authors are encouraged to exploit this information for quantitative analyses. As it stands, example tests are selected where already known phenomena are observed, without adding innovative insight.
- Also in the conclusions, the authors do not clearly highlight what is innovative in this work, but rather summarize the findings related to regression-rate characterization. Additionally, it is reiterated—several times throughout the manuscript—that more tests should be performed. Finally, no reference is made to the video acquisitions. I recommend reworking the conclusions after the manuscript has been revised.

Overall, I believe that this work has potential for publication. Even if additional experimental data cannot be obtained, several aspects should be revised to better emphasize the quantitative results that have actually been achieved. I commend the authors for their effort in processing experimental data, which are clearly non-trivial, as well as for the formatting and presentation of the manuscript. I remain available for further revisions.

Is the work clearly and accurately presented and does it cite the current literature?
Partly

Is the study design appropriate and does the work have academic merit?
Partly

Are sufficient details of methods and analysis provided to allow replication by others?
Partly

If applicable, is the statistical analysis and its interpretation appropriate?
Partly

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Hybrid Rocket Propulsion, Liquid Rocket Propulsion, Pyrolizing and Liquefying fuels, Hypersonics

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Reviewer Report 12 February 2026

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Rajiv Kumar
Birla Institute of Technology, Mesra, India

This paper deals about the use of paraffin wax as the hybrid fuel that were used in the form of slab and oxidizer were used was gaseous oxygen. The main objective of the paper is to obtain the regression rate at low as well as high oxidizer mass fluxes. Then they correlated these regression rates with the literature. The presentation of the paper is poor needs improvement in various sections which is as follows:
1. It is not clear why slab burning arrangements has been made for the study, as it does not gives real time regression rate.
2. The abstract presented do not gives any important information about the outcome of the paper except proving that regression rate follows the mass flux increase trend that is available in the paper. Thus, abstract needs to be re-written.
3. In introduction, it is claimed that stand burner used for solid propellant burning is similar to this slab burning of hybrid rocket. How it is beneficial to use slab burning in hybrid rocket is not clear. As here anyway oxidizer has to be injected into the rocket, instead of cylindrical grain, slab is used. Justify this.
4. Normally at the end of Introduction section, aim or objectives is provided but this paper donot have any clear presentation of the aim of the present work. Thus, it needs to be included.
5. Table 2; gives many numbers of experiments starting from 2022 to 2024; why these many experiments were needed?
7. Paper does not have experimental set up that is needed for clear understanding of experimentations undertaken.
8. Table 1 shows burn time as 10 sec but pressure time graph shown in Fig. 2 is only for 5 sec. How it is so?
9. Sequence of Fig. 4, 5 and 6 is not correct. Fig. 5 should be earlier than Fig. 4
10. Table 3 shows mass flux in the range of 6 to 15 kg/m^2-sec but the flow rate as given in Table 1 is 100 g/s then how mass flux is low within 6 to 15 kg/m^2-sec. It is not clear.
11. Why in Figure 7, error bar shows a large range, why its accuracy is so less?
12. Conclusions needed to re-written, current write-up are more general and is more about what would be done in future. But conclusions should be more specific to the work done in this paper

and their main outcome.

Is the work clearly and accurately presented and does it cite the current literature?
Partly

Is the study design appropriate and does the work have academic merit?
Partly

Are sufficient details of methods and analysis provided to allow replication by others?
Yes

If applicable, is the statistical analysis and its interpretation appropriate?
Yes

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Hybrid Rocket, Rocket Propulsion

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Reviewer Report 30 January 2026

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Mathieu Chartray-Pronovost
Polytechnique Montréal, Montréal, Canada

General comments:
Concerning the report questions;
The study design is appropriate, but its application seems to be too limited in scope, removing some of its academic merit. It is unclear what novelty this brings to the field of hybrid rocket engines (HREs) research. It seems the parameters tested were already tested by other groups, you cite them yourself in your paper. This can be fine if your results go beyond other author's, even for the same tests, but this is not the case. For example, a slab burner's advantage over traditional

strand burners is the optical access and crossflow effects, but you use that optical access only qualitatively. There is a wealth of quantitative data that could be obtained from your images; this paper does not present any of it.
The statistical analysis is lacking, but this is expected of slab burner experiments, as every test is time consuming and we cannot expect hundreds of tests. This is not a problem.
The source data on pressure is available, but no optical data (i.e. images) is present on your repository.

The paper itself is well written, and the experiments seem well designed and reproducible. However, more work needs to be done on analysis, and a lot more results can be extracted from your measurements.

Specific comments:

- In the introduction's second paragraph, it is written that HREs are simpler, safer and more cost-effective. But no reasons or descriptions are given for this. Notably, better cost-effectiveness is very debatable, considering HREs haven't been used commercially yet (outside of one-off launches).
- In the introduction's fourth paragraph, you introduce slab burners by comparing them to SRBs strand burners, but strand burners exist for HREs as well (i.e. 10.1016/j.fuel.2022.127152). The introduction of slab burners and their advantages is poorly made in this paragraph. Combining it with the subsequent paragraph and removing unnecessary information would help readability.
- On page 5, you introduce a "black pigment" for your fuel. What is the nature of this pigment? Does it affect combustion chemistry, structural properties?
- Page 5: There is a small typo. "a nitrogen flow purges the combustion chamber and **extinguish** the flame." It should be **extinguishes**.
- On page 5, you discuss of the residuals deposited on various surfaces of the chamber during the test, and you collect them and weigh them with the leftover slab to determine regression rate. As any analysis been done on these residuals? How do you know they are unburnt paraffin? They could be partially burnt paraffin or soot.
- On page 8, you say some tests were not considered due to "unsteady combustion or excessively long ignition transient". How did you determine if combustion was unsteady? And what is your cutoff for ignition transient time?
- Concerning the section on Internal ballistics visualization, and related to my previous general comment on qualitative over quantitative data; You say this is the main purpose of the test bench, but there is only qualitative data discussed. Why not get quantitative data? Most parameters discussed (flame thickness, soot emission in visible spectrum, regression rate) should be calculated, and can be measured using your images.

Figures 15 to 22 should be combined into a single figure, enhancing readability as a whole, and visualization of the discussed phenomena.

References

1. John J, Sharma J, Miglani A, Nandagopalan P, et al.: Structural characterization and regression rate of solidified ethanol fuels for hybrid rocket applications. *Fuel*. 2023; **336**. Publisher Full Text

Is the work clearly and accurately presented and does it cite the current literature?

Yes

Is the study design appropriate and does the work have academic merit?
Partly

Are sufficient details of methods and analysis provided to allow replication by others?
Yes

If applicable, is the statistical analysis and its interpretation appropriate?
Partly

Are all the source data underlying the results available to ensure full reproducibility?
Partly

Are the conclusions drawn adequately supported by the results?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: I have worked on slab burner experiments in the past, and am up to date on the current research as well as the foundations of hybrid rocket propulsion.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to state that I do not consider it to be of an acceptable scientific standard, for reasons outlined above.