Hybrid propulsion: an overview of the Onera activities

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Abstract
Onera has developed know-how of more than 40 years on hybrid propulsion concept based on theoretical, experimental and numerical approaches. The propulsive performance of a hybrid rocket depends directly on the solid fuel regression rate which needs to be increased for that technology to be competitive compared to other chemical propulsion systems. Liquefiable fuels, which undergo degradation to the gaseous phase by forming a thin, hydro-dynamically unstable liquid layer which is then atomized, provide regression rates 3 to 4 times higher than the values encountered with classical fuels. This regression rate increase is confirmed from static firing tests, flight tests and modelling.

1. Introduction

Liquid and solid space propulsion received strong investments to make them today nearly unavoidable for large space launchers and sounding rockets. However, each of them has significant drawbacks: cost, complexity and relatively low reliability and operation in case of liquid propulsion, and low specific impulse, no shut-down or thrust modulation capability and pyrotechnic security concerns in case of solid propulsion. These drawbacks may become more limiting when considering new transportation vehicles for space exploration missions or micro-gravity experiments. These applications will require efficient, safe and environmentally friendly propulsion systems, combined to a high level of performance, reliability and availability. One promising approach to provide sufficient thrust over weight (T/W) and throttling capabilities to enable to perform these flight missions is the use of hybrid chemical engines where a liquid oxidizer is combined with a solid fuel.

Although the hybrid propulsion concept is known for decades, it has never been the subject of thorough studies since Marxman's developments [1] in the 1960's. The demand for new small launch system could, today, justify maturing this technology. Hybrid propulsion applied to sounding rockets would allow reducing the costs of upper atmosphere experiments. Thrust modulation capability would allow space exploration vehicles to better reach their targeted landing area or orbit. Thanks to its safety and environmental friendly operation, this technology could also be used advantageously as a new approach to create propulsion power for air transport passenger vehicles and unmanned flying platforms using suborbital flight trajectory. Reviews of the state-of-the-art of hybrid propulsion have been already published by Kuentzmann and Sternfeld [2], by Altman and Holzman [3], by Humble *et al.* [4] and by Calabro [5]. The authors have described some past European and American flight tests and summarized the fundamental studies in a previous paper [6].

2. Hybrid propulsion concept and physics

Hybrid engine is an innovative propulsion system which combines a propellant in a solid state and a second propellant in a liquid state. The most often presented configuration considers an oxidizer (stored as a liquid, but rapidly vaporized in the forward dome of the motor, or gasified by flowing through a catalyst bed) which flows through long fuel channels and burns with the pyrolysis gases coming from the ablation of a solid combustible fuel. In this case, the solid fuel is cast in the combustion chamber referring to the solid rocket motor technology whereas liquid is stored in a proper tank referring to liquid propulsion technology (Figure 1).

Hybrid engines enjoy from a well-known safety level thanks to their simple structure and the wide range of inert propellants they can use. They can be throttled, restarted or turned off in case of an abort procedure. They have got appreciably high specific impulse associated to reduced costs and a reduced environmental impact, since fuels mainly burn into steam water and carbon dioxide. These advantages are detailed in Humble *et al.* [4].

In the combustion chamber, the liquid oxidizer flows down the port and reacts near the surface of the solid fuel. The engine performance results then from the development of the flow and the combustion in the long fuel channels and can only be modelled from a proper knowledge of the physico-chemical processes. The gaseous phase reaction first requires the sublimation of the fuel and its diffusion through the dynamic boundary layer up to the flame zone. The oxidizer is also diffusing towards the flame zone. After initiation by a pyrotechnic igniter, a fraction of the heat released from the combustion is transferred to the solid fuel interface by convection and radiation and allows its pyrolysis. Such a cycle makes from hybrid combustion a self-sustained phenomenon which occurs as a macroscopic diffusion flame and lets us foresee a dependence of the ablation rate towards heat and mass transfer processes [7].

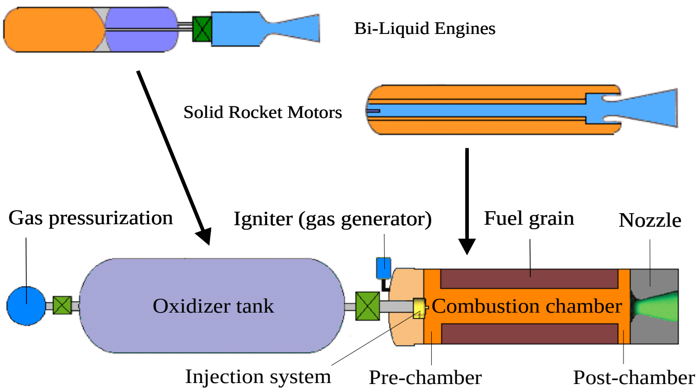


Figure 1: Hybrid propulsion concept

As opposed to solid propellant and liquid propellant motors, the amount of ablated fuel, and thus the combustion chamber oxidizer to fuel mixture (O/F) ratio, are directly linked to the heat get by the fuel grain from the reacting flow and are then varying down the length of the motor. Since the flame between oxidizer and pyrolysis gases is essentially conditioned by their diffusion towards each other, the regression rate is also mostly dependent upon the mass flow rate within the fuel channel. So, the fuel regression rate varies with mass flux and along the length of the combustion chamber following the relatively simple expression [3,4,7]:

$$\dot{r} = aG^n x^m \tag{1}$$

where $\dot{r}$ is the fuel regression rate (m/s), G is the total propellant mass flux (kg/m^2.s), x is the distance down the combustion chamber and a, n, m are the regression rate constants, characteristic of the propellants. Since G includes the mass flow from both the injected oxidizer and the fuel that has vaporized from the surface of the fuel wall, it increases continuously down the combustion chamber.

The combustion phenomenon is similar to that of a turbulent diffusion flame for which the flame zone is established within the boundary layer [8] (Figure 2) and corresponds to the coupling of the:

- Kinetics of the condensed phase pyrolysis;
- Homogenous combustion mechanism in gaseous phase;
- Convective and radiative heat transfers in gaseous phase;
- Mass transfer of the non-premixed chemical species.

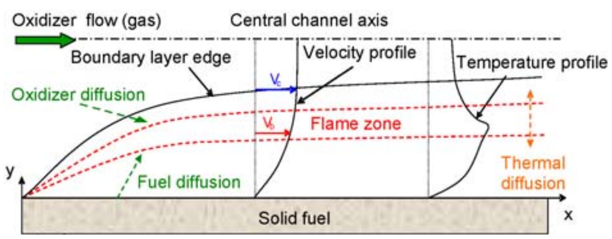


Figure 2: Hybrid propulsion physics [3]

This process can be treated by an idealized model which considers the flame zone as a point of discontinuity in temperature gradient and composition. In reality, the flame zone is thickened and both oxidizer and pyrolysis gases from the fuel are entering the flame zone by diffusing towards each other through the boundary layer. The combustion zone is established at the point where an approximate stochiometric mixture ratio has been achieved [4].

Hybrid chemical propulsion physics involve then many complex phenomena: fluid dynamics coupled with combustion, turbulence, spray atomisation and vaporisation processes, soot formation and radiation, fuel surface pyrolysis and fuel liquid film. The knowledge of the complex interactions between these wide-ranging physical phenomena is fundamental for the hybrid motor design. The solid fuel regression rate (eq. 1) is one of the most important values in the hybrid conceptual design process used to determine the propulsive performance. Today, its low value (1-2 mm/s for classical non-doped fuels and max. 5 mm/s for doped polymer-based fuels or wax-based fuels) associated to lower performance compared to other chemical propulsion systems blocks the maturing of this technology. To be competitive, a regression rate of the order of 10 mm/s is required. In order to reach this value, it is fundamental that a better understanding and modelling of the hybrid chemical propulsion physics is obtained to allow the necessary important conceptual and technological advances to be made.

3. LEX sounding rocket

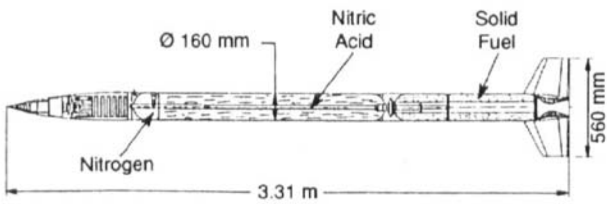
Intensive research on hybrid propulsion started at Onera as from 1956 at the prompting of Barrère and Moutet [9,10,11]. The program, called LEX for Lithergol Experimental, aimed at developing an autonomous rocket associated to reduced technological developments and a low cost production.

Six years later, Onera investigated all aspects of hybrid propulsion and developed the MT.27 hybrid engine using a hypergolic propellant based on nitric acid and an amine fuel. The combustion time of the engine was between 30 and 35 s for an operating pressure of 75 bar and a thrust of 10 kN at 150 ms, providing a total impulse of 100 kN.s. The most difficult aspect was to guarantee the thrust of 10 kN in 150 ms with a fuel port length of 800 mm and an initial diameter of the channel of 60 mm, which implies an almost instantaneous transition of the combustion gases from rest to a pyrolysis of 10 mm/s. This delay was obtained by adding a thin layer of hypergolic propellant type PPD (Para-PhenyleneDiamine). The oxidizer injection valve was also designed to provide two regimes allowing a reduced oxidizer flow rate during the ignition phase.

The MT.27 hybrid engine was integrated in the LEX sounding rocket. The first flight (LEX.01) occurred in April 1964 and was the first flight of a hybrid rocket in Europe. It was limited to 12 s of operation by reducing the oxidizer mass to avoid reaching populated area. The launch aimed to compare flight data to ground firing tests and the performances were found identical.

This first test was followed by three flights in June 1965 with the LEX.02 and four flights in November 1967 with the LEX.02 B’. Figure 3 shows the drawing of the LEX02 rocket and a launch on the Isle of Levant. The main features of the LEX02 rocket were [2]:

- Length: 3.31 m ; diameter: 160 mm;
- Liftoff weight: 75 kg including a payload of 5 kg;
- Hybrid propellant: 37.5 kg of HNO3 and 14.5 kg of NMTD (nylon-metatoluene-diamine);
- Prechamber operating from 50 to 10 bars and delivering 10 to 2 kN.



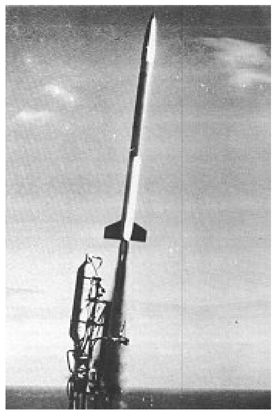


Figure 3: LEX02 sounding rocket section (left) and flight test (right)

The three flights in 1965 were successful with a combustion time of 33 s. Performances are in agreement with the ground firing tests, except the combustion time which is reduced by 2 s due to kinetic heating. Small instabilities are recorded during the last 2 seconds but without influence on the total impulse. The four flights in 1967, with improved mass ratio and aerodynamic drag coefficient, were also successful. The last one exceeded 100 km of altitude with a weight of 80.5 kg and a meteorological payload of 9.5 kg, which was a record for that time period. An instrumented parachute, dropped at the apogee, allowed wind measurements during the 31 min. of the descent.

The flight tests of 1967, which concluded the LEX program, proved that a hybrid engine with modulated thrust could be cheap and reliable if based on a hypergolic propellant with moderate specific impulse. The performance of this hybrid engine combined to its simplicity makes it the best candidate for sounding rockets. SEP made an extrapolation to 100 kN of the LEX.02 in the prospect of the industrial development of a sounding rocket carrying a payload of 200 kg to an altitude of 200 km. Twelve successful ground tests were carried out with this LEX.04 motor, which satisfied the performance and modulation specifications. No flights, however, were conducted with this motor.

4. Classical fuels

In the 1990s, ONERA has started again research activities on hybrid propulsion based on polymeric fuels. Static firing tests and flight tests took place and a 1D model was developed for the prediction of the fuel regression rate.

4.1. Static firing tests

The static firing tests were carried out on a reduced-scale motor [12] built with a pre-chamber in polyethylene (Figure 4). This pre-chamber with fuel fins has been used as thermal protection, to allow for better vaporization of hydrogen peroxide (H_2O_2) and to stabilize the flame. The injection of oxidizer (H_2O_2) was performed by means of an injector made up of three quintuplets, the central diameter orifice of which was used for the rapid extinction of the motor at the end of the test (cold gas injection). The ignition was carried out by a pyrotechnic igniter. Piezo-electric transducers were used to measure the pressure in the pre- and post-chamber, the oxidizer mass flow rate was measured by a Coriolis effect flowmeter and the surface regression was obtained by using an ultrasonic transducer. The first tests have been performed with a constant mass flow rate of H_2O_2. An example of measured results is displayed in Figure 5. Other tests have been performed with N_2O (pressurized or not) or H_2O_2 as liquid oxidizer and with either PE (polyethylene), HTPB (hydroxyl-terminated polybutadiene), PMMA (Plexiglas) or special compositions including energetic materials such as Alex (Nano-sized Aluminum powder) or Styrene balls [13,14]. Some of these results are provided in Figure 13.

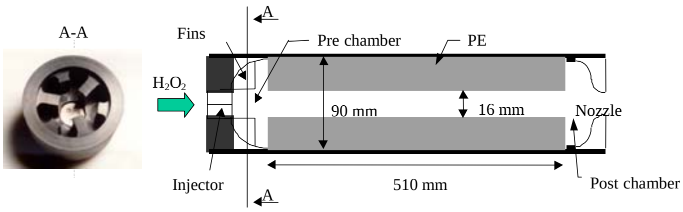


Figure 4: Structure of the first Onera hybrid motor

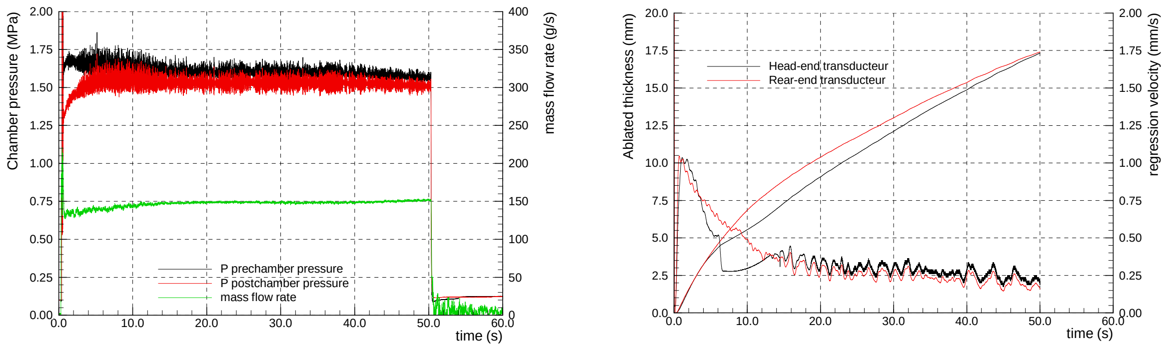


Figure 5: Results for one of the first test using the Onera hybrid motor (PE / H_2O_2)

4.2. FUSEX ground and flight tests

Since 2006, Onera is developing a hybrid engine for the student project PERSEUS, supported by CNES [15]. Several ground firing tests, using N_2O (nitrous oxide) and PE (polyethylene) as propellants, were carried out to develop the FUSEX motor and to reach the targeted performance of 840 N thrust and 1.5 kN.s impulse. The choice of the propellants couple was based on its excellent performances as a function of oxidizer to fuel ratio (O/F), which is variable during operation, and on the auto-pressurisation of nitrous oxide, avoiding a pressurising system. More details on the PERSEUS project and FUSEX engine are reported by Prévost *et al.* [16].

In order to respect the mass criteria, imposed by CNES (empty mass inferior to 6 kg), the motor is essentially built from titanium (Figure 6). The engine has a final mass of 5.5 kg and can hold 0.6 to 0.7 kg of N_2O. The dimensions are 120 mm in diameter and 600 mm in length. The fuel grain propellant has a diameter of 94 mm and the length is equal to 155 mm. It has 16 cylindrical ports with the initial radius of 2.4 mm at the head end and conical at the half end. An innovative, revolver like, system to load the combustible allows for the reloading of the engine after a launch when the rocket is recaptured. The only pyrotechnical element of the motor is the fuse. It consists of 2 g of solid propellant used to initiate the decomposition of the polyethylene and to open the valve that pilots the injection of the nitrous oxide. The valve/fuse coupled system (Figure 6) is designed and validated in order to assure a viable delay as to allow for the hot gasses to sufficiently degrade the polyethylene before the N_2O hits the surface. The operational envelope of the valve is found to be limited by a minimal temperature of 15 °C at pressure tank of 70 bar. Figure 7 shows the result of the ground firing test of the engine during the 1.2 s of operation. Thrust is found to be around 1.2 kN with a chamber pressure between 30 and 36 bar, suffering from instability amplitudes inferior to those observed in previous tests with similar configurations.

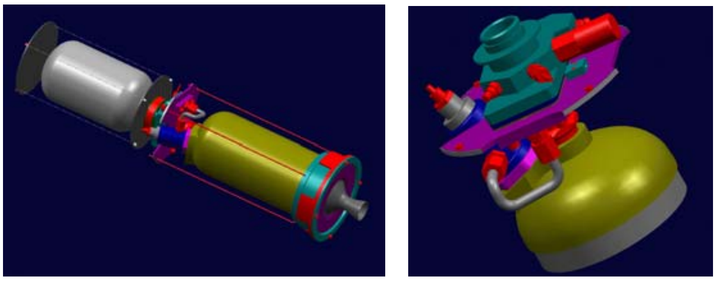


Figure 6: Overview of the FUSEX engine (left) and pyrotechnic valve (right)

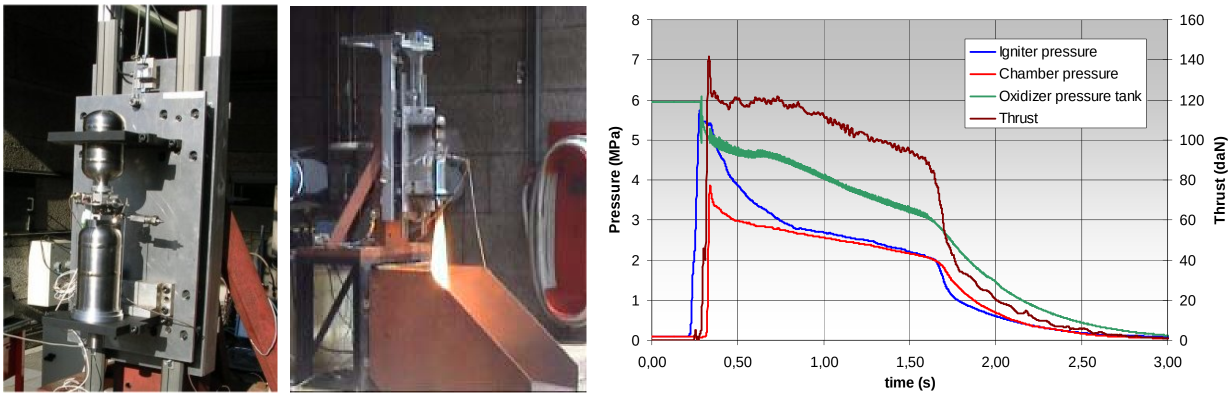


Figure 7: FUSEX engine before the firing and ignited and measurements during ground firing test

The FUSEX hybrid engine is integrated within the rocket manufactured by Planete Sciences. In August 2007, the FH01 rocket was tested in flight with success at La Courtine (Figure 8). The performances (Figure 8 and Table 1) are in conformity with the test of qualification (Figure 7) carried out in June 2007 at the Propulsion Laboratory [16]. The operating time of the engine is 1.1 s with a thrust of 1.65 kN allowing the rocket to flight during 40 s up to an altitude of 600 m. Three other successful tests (FH-02 to FH-04) were carried out in 2008 and 2009 at La Courtine and CELM. In particular, FH-04 is the first one with liquefying fuel (n-alcane: paraffin fuel). It reached an initial thrust of 1.2 kN for a total impulse of about 1.5 kN.s. Qualification ground tests with doped paraffin for improved performance were also performed recently as well as the development of a thrust modulation capability. A flight test with a two levels thrust modulation obtained from a rapid switch between two openings in the oxidizer injection valve will take place in August 2011. A review of the FH flight tests from 2007 to 2011 and the associated ground tests is planned to be presented at Space Propulsion in 2012.

Table 1: Performance of the flight test FH-01

	Main Goal	Test firing	Flight FH01
Initial Thrust (N)	**850**	**1 260**	**1650**
Total impulse (N.s)	**1 500**	**1 636**	**1609**
Burning Time (s)	**2**	**1,4**	**1,1**
Oxidizer to fuel ratio		**4,2**	**4**
Specific impulse (s)		**216**	**221**

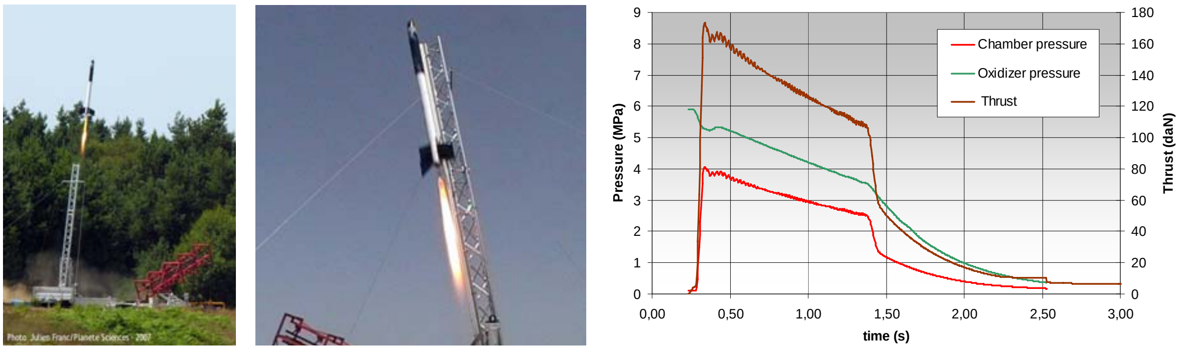


Figure 8: Flight test of the FH-01 rocket at La Courtine (PE / N_2O)

4.3. Regression rate modelling

Various kinds of approaches can be envisioned to improve the description of the flow, the combustion between the oxidizer and the fuel gases, the heat flux to the surface and the ablation of the solid fuel. A full Navier-Stokes scheme, with chemical kinetics, turbulence model, radiation model... taken into account, would be desirable [17,18]. This approach cannot be avoided if one wants to describe the strongly recirculating regions within the pre-combustion and post-combustion chambers. In the long fuel channels (with L/D of the order of 10) the radial gradients are prevalent and are controlling the chemical species diffusion and heat conduction processes. A parabolized approach can then be applied, which can take into account finite kinetics and turbulence flame interactions effects [19]. However, in the preliminary design process, when various outside diameters, numbers of ports, thrust evolutions (with of course the geometry of the perforation in constant evolution during the firing) and performances are seeked, it seems that a simpler approach could be useful.

The leading idea is to couple the hybrid combustion model developed by Marxman [1] with an integral description of the flow within the combustion chamber. According to Marxman, the assumption of a Reynolds analogy between the mass and heat transfers makes it possible to simplify the expression of the energy balance at the pyrolysis interface. The method is based on the assumption of a velocity profile and, as in an integral method for shear layer computation, on a 1D marching procedure down the length of the fuel perforations. The flame between oxidizer and fuel gases is assumed to be very thin, controlled by the diffusion process. The details of this regression rate formulation are provided by Lengellé *et al.* [19] and recalled by Pelletier and Maisonneuve [13].

Onera has developed the numerical code DEPHY whose main loop is intended for the space-time integration of the combustion integral model. The code is able to provide the regression rate evolution along the fuel grain and the influence of the thermodynamic conditions and of the geometrical parameters. Combustion properties, such as flame temperature, specific heat ratio, or molar weight are preliminarily computed thanks to COPELLIA, the Onera's thermodynamic resource. Steps of DEPHY's running are shown in Figure 9, from initialization to the end of simulation. Several fuel grain geometries are available under DEPHY so as to study their influence on performances evolution.

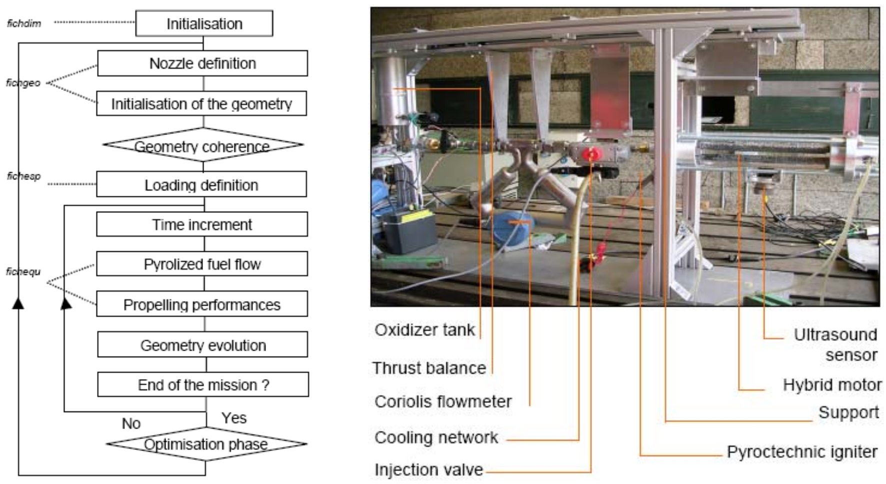


Figure 9: Organization of the DEPHY numerical code (left) and overview of the Onera test facility (right)

Pelletier [7] has run DEPHY on the JIRAD test case, a pure HTPB single-channel combustion chamber subjected to a 100 g/s mass flow rate of liquid oxygen (LOx). He also did a sensitivity analysis about the injection temperature of oxidizer, the chamber pressure, the heat of combustion and the global emissivity. Another comparison was made using Onera experiments carried out on a reduced-scale motor similar to the one presented in Figure 4 but with two cylindrical channels made of PMMA and with N_2O as oxidizer [13]. The test facility is shown in Figure 9. Two simulations have been performed with different values for the reactive flow emissivity (ε=0.1 and ε=0.2) as it cannot be easily evaluated. Figure 10 displays a comparison between the experimental instantaneous regression rate measured in the medium section and the simulated regression rate averaged on the fuel grain length. Simulation is in agreement with test data for ε=0.2. Increasing emissivity raises the regression rate but does not affect the shape of its curve.

Numerical modeling of the hybrid rocket engine is also the objective of two other research projects currently running at Onera. The first one, financed by the CNES, aims at modeling the ignition of the hybrid motor and the first instants of the internal flow behavior using CEDRE (ONERA code) with its existing modules and to define which model(s) need to be improved. The other activity takes place within the FP7 Collaborative Project ORPHEE, supported by the European Commission and coordinated by SME [20]. Onera is responsible for the extension of its existing regression rate modeling to treat the entire hybrid combustor with a special attention to the flame development and to the radiation effects to estimate the heat flux at the fuel regressing surface.

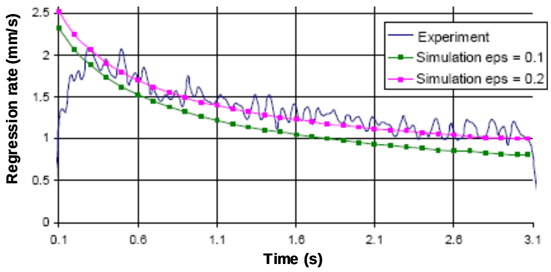


Figure 10: Instantaneous regression rate comparison between DEPHY results and Onera test case

5. Ways to increase the fuel regression rate

The low regression rate achieved with classical fuels is still the main shortcoming of the current hybrid technology. Typically, regression rates of polymeric fuels such as HTPB reach a couple of millimetres per second, what is too low to produce good thrust level. So, recent studies focus on how to improve the pyrolysis by the choice of the best propellant and geometry. Regression rate could be grown by increasing convective or radiative heat transfers from the flame to the fuel grain, even if the blocking effect will limit that growth beyond a critical value.

Russo Sorge *et al.* [21] investigated the effect of the oxidizer injection on the convective transfers by considering axial and radial injectors. They found that the conical axial injector performs better than the radial injector, at least for low oxidizer mass flow rate below a critical value. However, since the oxidizer mass flux in a real engine might vary around the critical value, the improvement could be limited. Lee *et al.* [22] proved that an induced swirl flow obtained by combining a swirl injector with an helical configuration of the fuel grain could be an effective way of increasing the turbulence level and the residence time of oxidizer in the solid fuel. Different configurations were tested and the authors found it was possible to double the regression rate. By combining a modification of the injection with an improvement of the reactive flow field, Knuth *et al.* [23] proposed another engine configuration characterized by a coaxial, coswirling, counterflowing vortex combustion field in a cylindrical fuel port. Fuel regression rates up to seven times larger than those in similar classical hybrids were measured. Even though the principle seems very promising, it is questionable for being use with liquid oxidizers, which would be needed to increase the oxidizer density, because the liquid film generated by the oxidizer flowing along the chamber walls might isolate the fuel from the central part of the engine.

Another possibility to increase the regression rate relies on energetic additives mixed with the classical polymer fuels. Evans and Risha [24] have tested the addition of nano-particles of aluminum and tungsten of the order of 100 nm within a HTPB fuel. For example, addition of 13% in weight of nano-sized tungsten powder to HTPB-based fuel resulted in an increase of 38% in fuel regression rate compared to the pure HTPB fuel. However, the use of metallic additives can also lead to very high flame temperature problematic for the motor and nozzle integrity, while droplets of metallic oxide would be detrimental for the specific impulse. De Luca [25] has tested magnesium and aluminum (AlH_3, called Alane) hydrides compositions as energetic molecules to be added to the HTPB fuel and showed solid fuel regression rates up to 2.5 times higher depending on the hydride mass fraction.

Alternative approaches using cryogenic solid fuels [26] have shown interesting improvements in regression rates (3 to 5 millimetres per second) thanks to mechanical regression but have since been discarded due to the associated disadvantages: cost, weight penalty for insulating and the inconveniences of handling these cryogens in the solid state. An interesting spin off from this research work was the notion of using liquefiable fuels [27]. An ideal candidate is paraffin for its high liquefiable behaviour (melting temperature below 100°C). The regression rate is improved due to the paraffin's ability to pass from a solid phase to a gaseous phase via an intermediate particularly non-viscous liquid phase. This leads to the formation of a hydro-dynamically unstable liquid layer on the melting surface of the fuel grain. Under precise conditions of viscosity, surface tension, and mass flow rate, this layer can be unstable so that liquid droplets are entrained in the reactive flow (Figure 11). For practical oxidizer flux levels encountered in hybrid rocket applications, droplet entrainment can dominate direct gasification. The atomization process is then at the origin of the large increase of the fuel regression rate compared to the classical fuel for which the pyrolysis is only due to evaporation. The first investigations of Karabeyoglu [27] allowed finding formulations offering regression rates 3 to 4 times higher than the values encountered to date. Figure 12 provides a picture of a hot-fire test using the Stanford Sub-scale Hybrid Test Facility and gaseous oxygen (GOx) as oxidizer, and the comparison of the regression rates measured with paraffin-based fuels compared to HTPB [27].

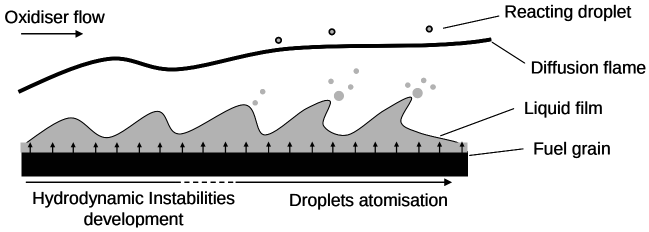


Figure 11: Karabeyoglu's schematic of entrainment process for liquefied fuels

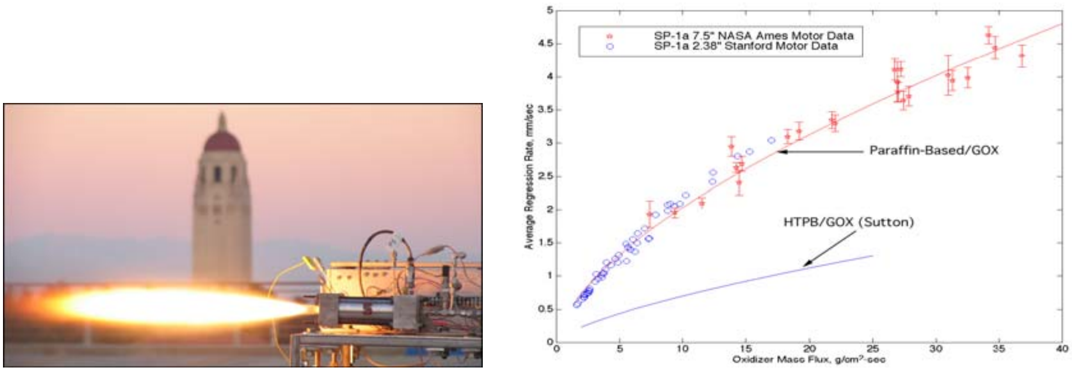


Figure 12: Hot fire test at Stanford University and comparison of regression rate for paraffin-based and HTPB fuels

6. Liquefiable fuels

6.1. Static firing tests

To asses the propulsion performances of paraffin-based liquefiable fuels, Onera performed numerous firing tests on a reduced-scale hybrid rocket (Figure 9) using N_2O as oxidizer with a mass flow rate of 170 g/s. Various fuel grains have been tested to check regression rate levels and general propelling performances: HTPB, PE, PMMA, special compositions including energetic materials such as Alex (Nano-sized Aluminum powder) or Styrene balls, and of course two paraffin-based formulations [14]. The initial diameter of the fuel grain was 14 mm and the burning time was about 3 s.

Figure 13a shows that the chamber pressure is decreasing after the very short transient regime due to ignition. The pressure decrease is due to the blow down of the oxidizer tank. Note that instantaneous curves on Figure 13a include pressure instabilities that are thus very low. Performance comparison is difficult since initial chamber pressure differs between those tests because the oxidizer tank was not thermally conditioned. Figure 13b illustrates the thrust levels reached during those seven firing tests. Thrust levels obtained with paraffin-based fuels are much more important than those measured with polymeric fuels, with an increase of about 200%. Because of the relatively close densities of the fuels tested, one can deduce that paraffin-based formulations demonstrate much higher regression rates. Figure

13c gives the instantaneous fuel regression rates obtained by ultrasonic measurements. All tests behave similarly showing a very high initial regression rate that fast decreases due to the opening of the fuel channel, indicating the influence of the gas mass flux. This is in agreement with Marxman's expression of the regression rate given by relation (1).

Regression rates found during experiments with paraffins are twice to three times higher than those obtained with usual polymeric fuels such as HTPB, PMMA or PE. The theoretical model developed by Marxman, where fuel degradation is supposed to be pyrolysis, can't explain such an increase in burning rate. This could only be explained by another degradation mode implying the thin melt layer above the solid fuel grain.

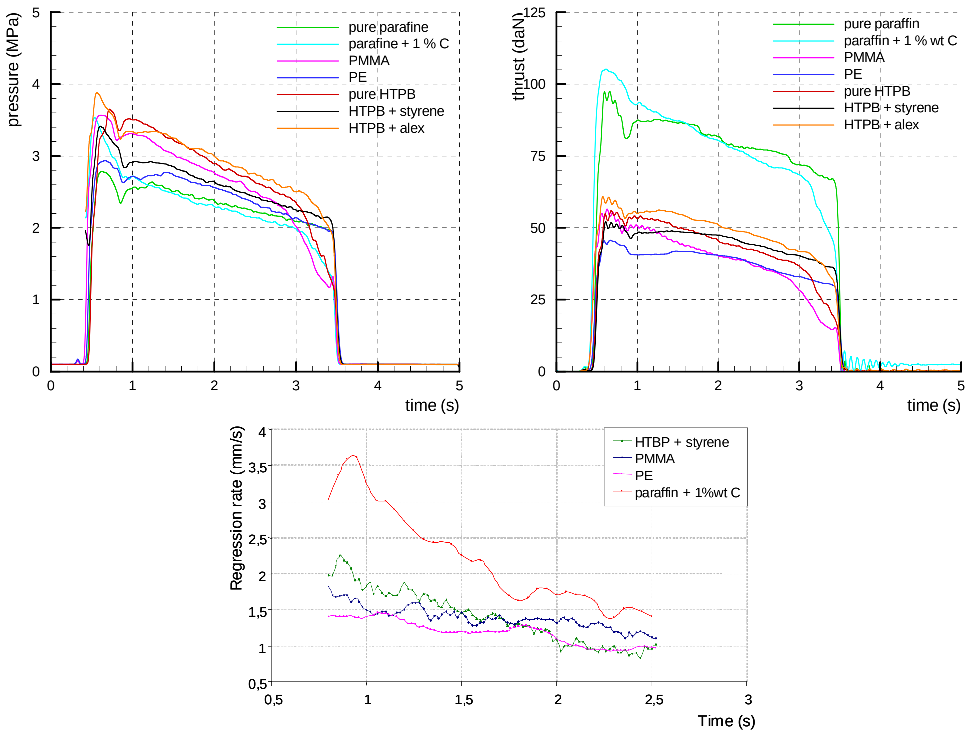


Figure 13: Evolutions of chamber pressure, thrust level and regression rate for different fuel formulations

6.2. Regression rate modelling

A 0D model has been developed by Pelletier [14,28] to accurately predict regression rate of paraffin-based fuel compositions, and more broadly speaking of liquefiable fuel. A liquid film is supposed to appear owing to a fusion process, thus creating a liquid interface between the solid fuel grain and the reactive gas flow. During the regression process, the liquid film is assumed to be always fed by the fuel grain fusion, while vaporization depletes the liquid film. When subjected to a gas flow, a liquid film may develop linear hydrodynamic instabilities due to infinitesimal perturbations which may grow in amplitude and become strongly non-linear. The liquid-gas interface is then distorted and has a wavy shape from which liquid droplets can be carried away in the gas core (Figure 11). This dynamic phenomenon is believed to be the inception of the regression rate boost.

Pelletier [28] applied first the hydrodynamic linear stability theory to check whether the liquid layer generated by phase transition could be destabilized and distorted when subjected to small disturbances. When compared to other liquids, paraffin is associated to higher hydrodynamic instabilities for the same gas flow conditions. This is explained by the very interesting properties of n-alkanes in terms of dynamic viscosity and surface tension whose relatively low values contribute to a better destabilization of the liquid film. All those results indicate that hydrodynamic disturbances should be strong enough to potentially lead to the atomization of the fuel liquid layer and thus conduce to a major increase in the fuel regression rate.

The fuel regression rate can be formulated in terms of both vaporization and atomization contributions. Based on the work by Gater and L'Ecuyer [29], a semi-empirical law was derived that links the atomization regression rate to the total regression rate which, combined to the mass and energy conservation laws, allowed finding an implicit expression of the atomization regression rate [28]. Surface tension and dynamic viscosity of the liquid phase tend to decrease the atomization regression rate, as well as a thicker liquid film. On the other hand, atomization is increased by a higher friction coefficient and thus by the rugosity of the liquid film. Figure 14 provides the total regression rate, and its atomization and vaporization contributions, in function of the gas mass flux. The classical regression rate formulated by Marxman and taking into account only the fuel degradation by pyrolysis is also provided. For high gas mass flux, regression rate of liquefiable fuels can be increased up to 3-4 times compared to classical fuels.

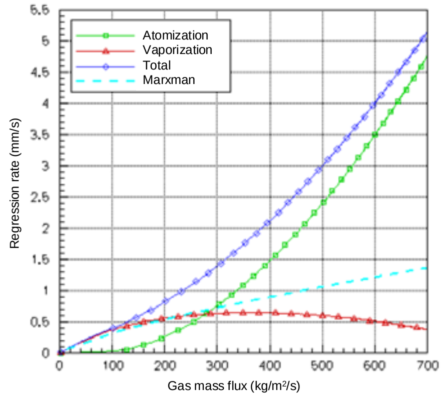


Figure 14: Total regression rate and its contributions in function of the gas mass flux

To validate the regression rate modeling for liquefiable fuels, Onera has built the HYCARRE facility (Hybrid Combustion Analysis for Regression Rate Evaluation) [14,28,30]. This set-up (Figure 15) is intended for reproducing the thermal and dynamic environment actually encountered by the fuel grain in a hybrid rocket motor, without combustion. To achieve this, a solid fuel sample is tested in a 2D test-section subjected to a hot gas flow whose temperature and mass flux are accurately controlled. Hot gas is produced by a hot gas generator fed in gaseous O_2/H_2. However, hot gas temperature is too high, whereas gas mass flux is too low. A precise flow of nitrogen is therefore used as dilutant to reach every operating point and an adiabatic transition is implemented between the hot gas generator and the test-section to provide uniform thermal and velocity profiles. The test-section has two side plane-parallel optical quality portholes allowing a flawless visualization of the hot gas flow and of the surface phenomena occurring during fuel regression process. It is also instrumented for pressure and temperature unsteady measurements and for PIV and flow visualization with a high-speed camera. Finally, ultrasonic sensors allow measuring the instantaneous regression rate.

The first test campaign performed for one paraffin-based formulation, one flame temperature and one gas mass flux aimed at measuring the liquid film thickness and the regression rate by optical diagnostic and ultrasonic probe. Both results are well matching and the experimental regression rate is also comparing quite well with the 0D model developed by Pelletier as indicated in Figure 15.

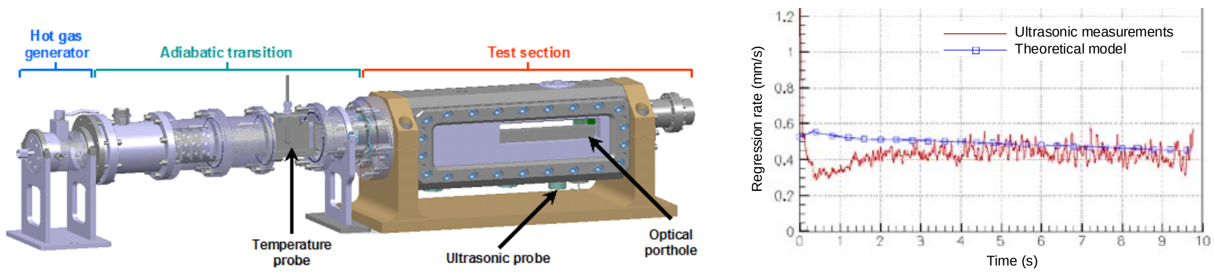


Figure 15: HYCARRE facility and comparison of the measured and computed (0D model) regression rate

Although the 0D analytical model based on the mass and energy conservation laws at the interface between the liquid and the gaseous phase gives a quite good estimation of the regression rate of the liquefiable fuels, it can not be used to define the internal geometry of the fuel grain. Moreover, the 1D code DEPHY can not be used either since the degradation of the liquefiable fuels is different than for the classical polymeric fuels. Onera is then currently developing, in the framework of the PhD thesis of J.-Y. Lestrade supported by CNES, a 1D model adapted to the liquefiable fuels and based on an integral description of the aerothermical gaseous flow inside the fuel channel coupled to a one equation model for the thin liquid film. Because of the complexity of the different phenomena involved (atomisation, gasification, surface regression, ...), the development of the new 1D model is divided in several steps. Lestrade is considering first the particular case of a 2D planar flow without combustion for which the regression process in only due to the thermal and the mechanical phenomena [30]. This first step is justified since the experiments to validate and understand the physical phenomena are easier to set up without any combustion process and can make use of the HYCARRE facility. To obtain the instantaneous thicknesses of the solid and liquid phases of the fuel sample from the ultrasonic sensor data, temperature profiles in these two phases and the evolutions of sound velocity with the temperature are needed. The evolution of the speed of sound of the paraffin is determined experimentally for different temperatures, in both solid and liquid phases, using an ultrasonic sensor fixed to a sample whose length is well known [30].

7. Conclusions

New transportation vehicles for space exploration missions or micro-gravity experiments would require simplified, low cost, faster and thrust modulated operations combined to a high level of performance, reliability and availability. These capabilities could be reached through hybrid propulsion which combines a solid fuel with a liquid oxidizer. However, the hybrid propulsion concept was never been the subject of thorough studies since Marxman's developments in the 1960's. The demand for new small launch system could today justify maturing this technology.
Onera has developed a know-how of more than 40 years on hybrid propulsion concept based on theoretical, experimental and numerical approaches. The first European hybrid rocket (LEX) was launched by Onera in 1964 followed by 7 other successful flights in 1965 and 1967.

In the 1990s, Onera has started again research activities on hybrid propulsion based on polymeric fuels and more recently on liquefiable fuels. A large database of static firing tests performed at the Propulsion Laboratory is available for different operating conditions and fuel compositions. Some flight tests took also place recently within the Perseus programme. Finally, appropriate models are available on under development for predicting the regression rate of classical or liquefied fuels.

Different types of fuel formulations have been considered in the past with a current focus to the liquefied fuels, and in particular the paraffin-based compositions. Those fuels, stored under solid phase, undergo degradation to the gaseous phase very different from usual polymers, because they form a thin, hydro-dynamically unstable liquid layer on the melting surface of the fuel. The atomization of the liquid film is then at the origin of the large increase of the fuel regression rate compared to the classical fuel for which the pyrolysis is only due to evaporation. Different research groups, including Onera, have measured regression rates 3 to 4 times higher than the values encountered to date.

The current research is oriented towards a better knowledge of the physical mechanisms behind this regression rate increase, the development of a 1D model for the regression rate and the improvement of the fuel performance by using additives or other liquefiable fuel formulations.

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