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SRM Ignition Study at Lab-Scale

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Abstract

This paper presents the approach developed at ArianeGroup for studying the grain ignition in Solid Rocket Motors. A focus is made on the small-scale SRM and on the different characterisation stages needed to perform an ignition calculation. The first step consists in characterising the thermal properties of the propellant as the ignition results in the energy balance between the heat flux received at the surface and the conduction in the material. The second step addresses the determination of the ignition delay for a small sample of propellant given a direct heat flux. A first validation of the numerical model is obtained with the simulation of such tests. A dedicated test was designed to measure the flame spreading velocity over the propellant surface sample. As for the ignition time, the model successfully predicts the measured velocity. Finally, it is applied to the simulation of the ballistics of a small-scale motor. Understanding elements were obtained on the physics involved in the ignition process. This last stage validates the overall approach and allows the use of the model to the simulation of the full-scale SMR ignition. All the methodology steps are illustrated in the ignition of an HPTB/AP/AL composite propellant. Finally, the model is successfully applied to the ignition of a BATES grain.

Keywords: Ignition modelling, Ignition time, Flame spreading, SRM

Nomenclature

Ap	Pre-exponential factor
Eg	Activation energy in the gas phase
Ep	Activation energy in the solid phase:
Cp	Specific heat
$\dot{m}_p$	Instantaneous Propellant mass flow rate
Q_s	Heat release by surface reactions
R	Perfect gas constant
T	Temperature
α	Thermal diffusivity of the propellant
λ	Thermal conductivity
Φ_{conv}	Convective flux
Φ_{flam}	Flame flux
Φ_{rad}	Radiative flux
ρ_p	Propellant volumetric mass
$\cdot_p$	Relative to propellant

Acronyms

AP	Ammonium Perchlorate
HTPB	Hydroxyl-Terminated-Poly-Butadiene
MF	« Mesure de Flux » (Flux measure)
SRM	Solid Rocket Motor

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1. Introduction

Transient phases during Solid Rocket Motors (SRM) operating have to be studied with a specific care and modelled with accuracy to predict the motor ignition. Regarding these events, ignition is a critical phase: pressure oscillations can induce strong mechanical stresses into the engine structure [1]. ArianeGroup has developed a dedicated approach based on experimental characterizations and numerical simulations to better understand and master physical phenomena involved in the ignition of SRMs. This paper presents the different steps required to simulate the ignition of a lab-scale test motor, hereafter called “NMF”, an upgraded version of the MF test motor. The considered propellant is an aluminised composite propellant. The oxidizer loading is composed of ammonium perchlorate (AP) and the binder is based on a standard HTPB rubber in which aluminium particles are added. The aim of the study is to validate the numerical modelling of the ignition phase and to understand how to process data in the scaling-up from elementary characterization of the propellant to the simulation of the experimental small-scale motor NMF.

Ignition is a transient phenomenon [2] that can roughly be divided into two parts. Firstly a thermal flux heats up the propellant surface. Then the heat diffuses inside the material. It is generally considered that the propellant remains as “inert” and no chemical reaction can be clearly identified. When its surface temperature is sufficiently high, the ignition can take place. It is characterized by the occurrence of chemical reactions at the propellant surface and the production of gases that will react and generate combustion products. That transient step finally results in the stationary combustion of the propellant. A detailed description of the phenomenon is proposed in [3] by Gallier *et al.* where the ignition process is simulated at a mesoscopic scale representing the loading components of the propellant.

In order to correctly describe these physical phenomena, ArianeGroup develops a specific approach to consolidate and validate the numerical tools which are used in the simulation of the ignition of solid rocket motors. For this purpose, small scale motors are fired and their ignition are deeply analysed. In order to acquire a correct restitution of the ballistics, a first step is dedicated in the characterization of the thermal properties of the propellant. Density, thermal conductivity and specific heat are assessed at room temperature and ambient pressure. This stage is essential for any further modelling subsequent of the thermal behaviour of the solid propellant. The second step regards the determination of the ignition time for a small sample of propellant subjected to a specified heat flux. Numerical models used for the ignition are then tested on these experimental data. Based on the resolution of the heat transfer equations into the solid material. The energy balance at surface is assessed with more or less accuracy which allows reproducing the surface temperature evolution. These specific models are of prime importance to correctly describe the physics of the ignition. Such models are implemented into the CFD code developed by Onera [4] and preferentially used by ArianeGroup for the ignition studies. However, available models require the robust determination of a set of parameters. The third step consists in the simulation of the flame spreading at the surface of the propellant. A dedicated experimental set up was designed to access this information and the closure of the model is ensured by numerically obtaining the measured flame spreading velocity. The last stage considers the application of the identified model to the ignition of a small-scale study motor. It consists in a 7kg cylindrical grain with a central bore. The igniter is a small micro-rocket with 6 blowholes. Preliminary calculations aim at defining the mass flow rate and the temperature of gases of this igniter. A 3-dimensional numerical simulation is then performed to study the ignition of the grain and provide a better understanding of the physical phenomena.

All the methodology has been successfully tested with a non-aluminized propellant. A presentation of the logic and the results can be found in [7]. The present study is an application to a specific HTPB/AP/AL composite propellant with up-grades of the test bomb MF.

2. Ignition modelling

All the numerical simulations presented in this study are performed with the in-house Onera code CEDRE. Compressible Navier-Stokes equations with two equation turbulence model are solved using a finite-volume technique on unstructured mesh. A RAMS approach for the gas and condensed phase is considered and calculations are performed at second order accuracy in space (Roe scheme) and first order accuracy in time with an implicit scheme. Dedicated models have then been implemented to describe the non-steady ignition of the propellant. Two more or less complex models have been developed and integrated into the numerical tool by Onera. They will be respectively referred as model A and model B. Some details can be found in [5]. Both considered the resolution of the heat conduction into the inert materials.

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2.1 Thermal consideration

The standard equation of heat diffusion is associated to the energy equation into the propellant. This material is modelled as homogeneous, that means that all the structure of the composition propellant (i.e. AP loads) is not considered. For model A, the thermal equation can be written as, in a one-dimensional formalism:

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial y^2}$$

where α is the thermal diffusivity of the propellant.

Model "A" describes the ignition phase in an unsteady way, but the solution of the thermal transfer equation does not allow to reach the steady state since it is not stabilized by the convection term related to the propellant combustion rate. This limitation is removed in model "B" which solves the complete equation that translates the unsteady heating of the propellant by conduction and its surface decomposition at combustion rate V_c :

$$\frac{\partial T}{\partial t} + V_c \frac{\partial T}{\partial y} = \alpha \frac{\partial^2 T}{\partial y^2}$$

At the propellant surface, for both models, the conductive thermal flux of the material is balanced by fluxes from the gas phase (convective and radiative fluxes) and the heat released by the propellant degradation at the surface:

$$\lambda_p \frac{\partial T}{\partial x} = (1-\beta)\Phi_{flam} + \beta(\Phi_{conv} + \Phi_{rad}) + \dot{m}_p Q_s$$

where β is a parameter that can switch from the non-stationary state during the ignition to the stationary combustion state.

2.2 Flame structure of the ignition models implemented in Cedre

The first model, named "A" model, is built on a simple description of the ignition process. The total heat flux diffuses into the material that yields to an increase of the surface temperature. The mass flow rate is then modelled by an Arrhenius law:

$$\dot{m}_p = \rho_p A_p e^{\left(\frac{-E_p}{RT_s}\right)}$$

This indicates that no flux from the propellant flame is considered and β is taken equal to 1. The ignition occurs by comparing the surface temperature in the reactive case (with the above definition of $\dot{m}_p$) and in the inert case (i.e. without any mass rate but the resolution of heat transfer at the propellant surface). When the difference between the two surface temperatures evolution excides a given criteria (5% for instance), it is assumed that the propellant locally ignites. The complete combustion is reached after an additional time to reach the stationary combustion state. During this time, a linear evolution of the mass rate is assumed.

The model "B" is more representative of the complexity of the propellant flame but it assumes like model "A" that the propellant is a homogeneous material. This approach is unable to describe the small flame structure that takes place at the propellant surface. Neither the premixed flame at the AP loads nor the diffusion flame between the HTPB degradation and the AP combustion product gases are considered. Whatever, a general evolution of the temperature is assumed from the propellant surface to the combustion gas. Without entering into details, an additional equation is added to describe the overall reactions in the gas phase. A premixed flame is then considered through a second Arrhenius law and its associated E_g activation energy in the gas phase.

To summarise, the ignition models require the fixing of three parameters (A_p, E_p and Q_s) for the model "A" and four parameters (the three previous ones plus E_g) for the model "B". An important task is devoted to the determination of these parameters so that the models can describe the ignition of the propellant in term of mass rate evolution when the material passes from an inert state to a reactive state. Hence, the determination of the model parameters is based on experimental data.

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2.3 Radiative and convective fluxes

The global flux received by the propellant can be split into two contributions. The major one is provided by the convection at the propellant surface. As a detailed description of the boundary layer could be exhaustive in term of number of cells, a dedicated boundary layer condition has been introduced into the numerical code to correctly estimate the heat exchange coefficient '*h*' thanks to a dedicated boundary model. It then provides a correct estimation of the convective heat flux. The radiative solver used in this study is based on a discrete ordinate method. It was specifically developed by Onera to solve radiative problems applied to solid propulsion [6]. It implies the determination of radiative properties for the gas phase as well as for the particle phase as it is mandatory for the propellant studied in this paper.

3. Propellant characterisation

This study considers a AP/AL/HTPB composite propellant. Aluminium is added to the formulation so that two-phase effects are considered. As the combustion of aluminium droplets generates small alumina smokes, the condensed phase is treated as the gas phase. There is no drag forces that apply on particles to define their trajectory. Particles convection is similar to the gas one. Nevertheless, the determination of the radiative flux is taken into account by the radiative solver. Hence, gaseous molecules and alumina smokes are at the origin of the radiative flux. When they are present, particles generate the main part of the radiative flux. It can be compared to the convective flux with equivalent values.

3.1 Thermal properties

The evaluation of the thermal diffusivity and effusivety requires the knowledge of the propellant volumetric mass, thermal conductivity and specific heat. The next table summarizes the values of the thermal properties used in this study:

Table 1 : thermal properties of the tested aluminized propellant

density (Kg/m^3)	~1800
Specific heat (J/Kg/K)	~1200
Thermal conductivity (W/m/K)	~0.5

3.2 Experimental "Ignition delay / Flux" test bench

The ignition times are crucial data to build the ignition models with the fixing of the model parameters. The BALBEC (Banc d'Allumage Balistique et Combustion) test bench has been developed by ArianeGroup to obtain ignition delays depending on various radiative fluxes. The radiative flux is provided by a CO_2 laser and can spread from 0.5MW/m² to 1.5 MW/m². Before the test, the power provided by the laser beam is tested and calibrated on a specific propellant. The following figure illustrates the test bench. The ignition of the propellant sample is ensured by the laser beam. A specific power was selected in the range of those that are encountered in a SRM (roughly 1MW/m²). The ignition delay is then determined when the light starts to increase significantly. The flux received by the sample is estimated considering the power emitted divided by the total surface impacted by the laser beam. The beam surface is measured before each firing on a PMMA sample. The ignition is recorded by a high speed camera.

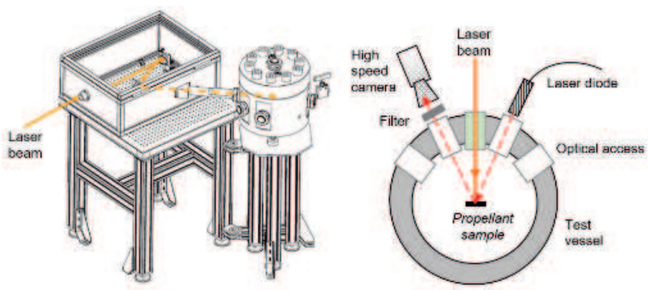

Figure 1 : Ignition test bench BALBEC
(general view and location of instrumentation for flame propagation measurement)

Thanks to the BALBEC test bench, the ignition delay is measured for three different heat fluxes. The results are reported to the next figure. In a log-log representation, the experimental data are located along a straight line whose slope of -2 is characteristic of the evolution of the ignition times with the flux.

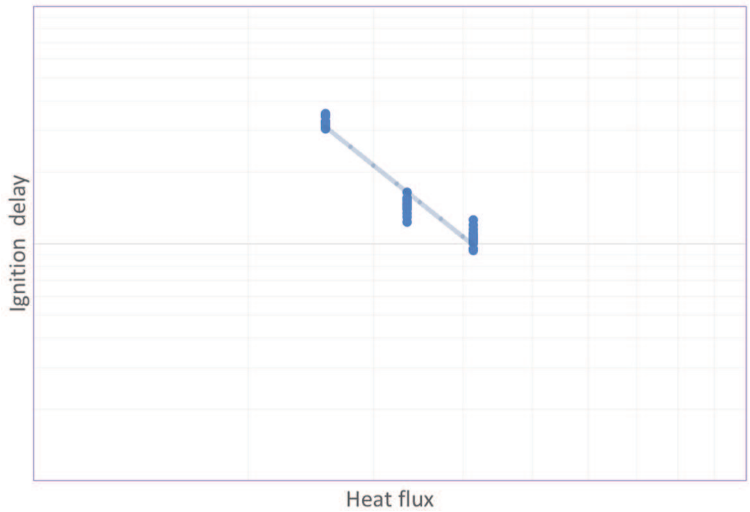

Figure 2 : Experimental ignition delay vs. laser heat flux

4. Parameters determination

This phase is of prime importance to define the ignition model. It is based on the exploitation of experimental data such as ignition delay. These data are completed by the evaluation of the flame spreading velocity over the propellant surface. The goal is then to find an optimized set of parameters that correctly estimates all the experimental results.

4.1 Ignition time test exploitation

From the exploitation of the ignition delay results, it is possible to access the knowledge of the parameters required by the different models. It has to be noted, that the set of parameters obtained for a model “A” cannot be applied directly to a model “B” and a new evaluation phase has to be performed. A common way to find the values of parameters lays on a least square minimization optimization. To achieve this goal, the two models were introduced in an in-house optimization tool. This was applied to the present study, but depending on the bounds for the solutions imposed in the procedure, several sets of parameters can be found. Unfortunately, we reach the limit of such an approach at this stage. An illustrative case is proposed considering the model “B” where the best results are reported. The ignition delay found by the optimization process is compared to the ones measured with the BALBEC test bench. All the data are non-dimensioned by the experimental delay obtained for the intermediate flux.

As it can be seen, a poor agreement is observed for the lowest flux. No explanation is available to justify why the experimental result provides such a long ignition delay. For intermediate and high fluxes, the agreement is rather good.

Table 2 : normalized experimental ignition delay and application of model B
(delay are normalised by the medium flux result)

Flux	Experimental	Model “B” estimation
Low	2.26	1.60
Intermediate	1.00	0.98
High	0.72	0.67

The application of the parameters set to the prediction of ignition delay is plotted on Figure 3 and compared with the experimental results.

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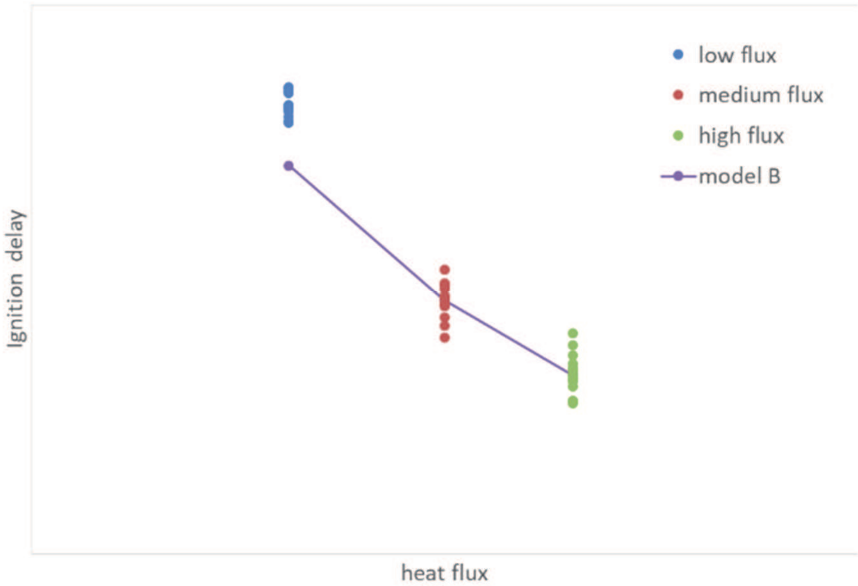

Figure 3 : Non-dimensioned ignition delay vs. total non-dimensioned heat flux for the experimental data and application of model B

4.2 Flame spreading exploitation

For this experimental test, the test bench BALBEC is used to ignite and record the expansion of the flame over the propellant surface. The Figure 4 presents a sketch of different views of the ignited propellant surface. For a better identification, the ignited surface is materialised by a yellow circle corresponding to 10mm, 20mm, 30mm and 40mm diameter. The propellant sample is ignited at its centre by a laser beam. After the ignition detection, the laser is turned off and a self-combustion of the propellant occurs. One observes the propagation of the flame over the surface according a disk whose diameter increases regularly with time.

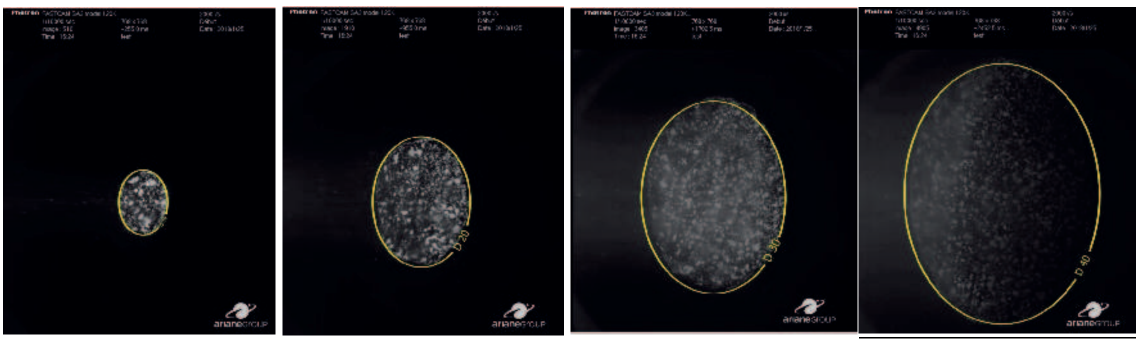

Figure 4 : Pictures of the flame spreading at different times

By analysing the movie when the ignited surface crosses the yellow line, it is possible to determine the size of the disk vs. time. This information is plotted on Figure 5 and derivation gives a value of 7 mm/s for the velocity.

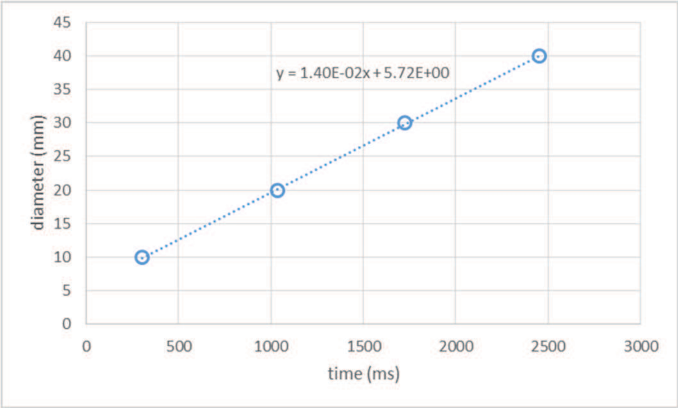

Figure 5 : Evolution of the disk diameter

A restitution of the flame spreading test was performed with the Onera code Cedre. A 2D-axisymmetric regular mesh is supposed to describe the aerodynamic field composed by 5600 cells. Boundary layers are represented by ambient air conditions with a pressure of 1 bar. The last boundary layer represents the propellant surface and is divided into two parts. The first one characterized by a length of 5mm corresponds to the surface already ignited (representative of the laser beam size). The mass flow rate is representative of the self-combustion of the propellant for that pressure. The gas is ejected at the temperature of 3100K obtained from a thermo-equilibrium simulation (in-house code). The second part of the domain represents the surface that is about to ignite. A model "B" is applied with the parameter set defined by the exploitation of the ignition delay tests. As it is supposed that the convective flux is reduced (gas is ejected from the ignited surface in a perpendicular direction of the spreading one), the radiative solver REA [6] is activated. The goal is to verify if the numerical simulation correctly estimates the total heat flux generated by the hot gases of the flame.

The Figure 6 shows the computational domain with the location of the boundary layers. The data are as follows:

- Mass flow rate : 4.5 kg/m2/s
- Gas temperature of the combustion products : ~3100K
- External gas temperature : 300K
- Pressure : 1 bar

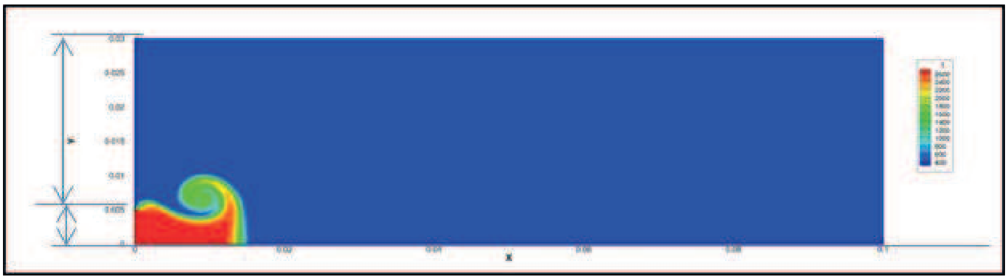

Figure 6 : Calculation domain (simulation at 2 ms)

Radiative flux is obtained by considering the following gas species mixture: ($CO/CO_2/H_2/H_2O/HCl/N_2$).

The next figure shows the column of hot gases coming from the ignited surface. With time, the thickness of the burning surface increases. By deriving this thickness, it is easy to find the corresponding flame spreading velocity.

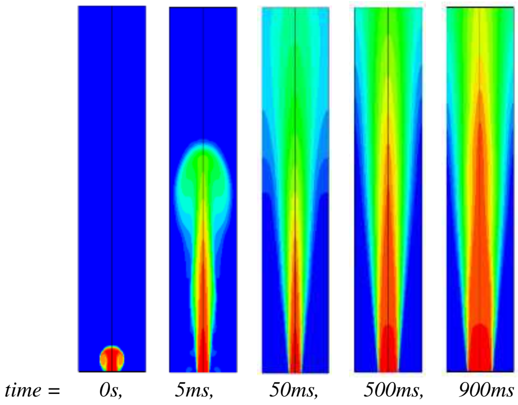

Figure 7 : Temperature field showing the enlargement of the ignited propellant

Two experimental tests were performed and both provided very similar results. The time period is characteristic of a self-propagating flame (laser off). The laser extinction is not taken into account in the numerical simulation. It is simply assumed that a reduced zone of the overall surface has been already ignited. After a rapid lag of time corresponding to the heating of the non-ignited part, one can observe a regular growth of the ignited surface. At 3s of simulation, the previous tendency disappears and a rapid increase is observed showing the ignition of the all propellant surface. The first stage is plotted on Figure 8. The velocity is given by the slopes of the curve. A velocity of 7.5 m/s is found for the numerical simulation to be compared to the experimental value of 7m/s. The similarity of the two velocities demonstrates that the model can correctly predict the flame propagation phenomenon.

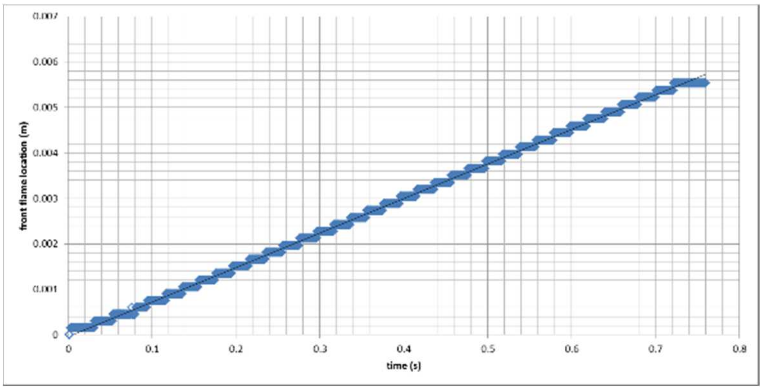

Figure 8 : Position of the limit of the ignited zone during the simulation (AP/AL/HTPB composite propellant)

5. Small-scale firing test

Thanks to the flame spreading test, the proposed parameter set was validated in the presence of a radiative stream. The selected parameters are then able to correctly predict the ignition time under a given flux. Moreover, the proposed model can also forecast the dynamics of the flame on propellant surface. Before applying this approach to the simulation of a full scale SRM, it was applied to the exploitation of a representative small-scale SRM. To achieve such a goal, a solid grain with central bore is fired in the NMF test bomb. The final verification aims to correctly describe the ignition of the grain. This is done thanks to the comparison of the ballistics and the total heat flux at the propellant surface.

5.1 NMF motor

The experimental test motor “Mesure de Flux (MF)” was designed to study the ignition of a solid grain [7]. An upgraded version was designed by modifying the inner geometry of the grain. The geometry is cylindrical with a central bore with 4 plane parts to be equipped with 4 fluxmeters each. The total length is 350mm for an outer diameter of 170mm and an inner diameter of 116mm. The overall mass of propellant (depending on the formulation) is around 7kg for an aluminized propellant. Originally, the motor is equipped with 16 fluxmeters to access the total and radiative fluxes along the central bore as shown on Figure 12. This new measurement equipment is of prime importance for the

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study of ignition phenomena. For the first time, a direct comparison between the heat fluxes recorded during the firing test and its numerical simulation is proposed.

As it can be seen of the Figure 9, 16 locations of heat fluxes measurements are available. As we expect to measure both radiative and convective fluxes, two lines were dedicated to each type of flux. As the igniter is composed of 6 events equally disposed on a cone, the solution was to consider 2 lines of 4 flux devices in line with the igniter plume and the last two lines in the intermediate zone between two plume lines.

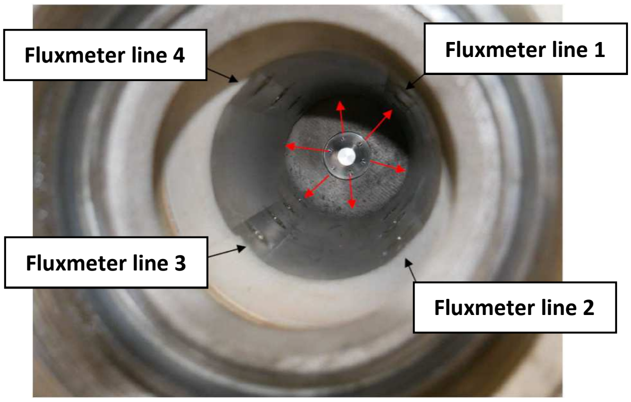

Figure 9 : View of the grain with the location of the 16 fluxmeters and the igniter

The ignition of the grain is ensured by a small grain of non-aluminized propellant. The hot gases generated during the operating of the igniter are ejected through 6 small blowholes and then form 6 plumes in the combustion chamber that will impinge the inner surface of the main grain. It ignites in its turn mainly due to the convective fluxes.

To anticipate the firing of a HTPB/AP/Al composite propellant in the NMF device, a preliminary firing was performed with an inert grain. The first goal was to validate the new procedure of the grain manufacturing and the placement of the traverses bore to receive the heat flux measurement devices. Due to the reactivity of the propellant to the static electricity and its strain sensibility, it must be bored when removed from the metallic bomb structure. A specific attention must be payed to respect the passage of the heat flux devices and ensure the correct assembly of the captors on the NMF structure. The second purpose of this test is to check all the measurements during a firing, and especially during the ignition phase. The heat-flux device are the tested in the presence of the hot gases provided by the igniter jets.

Table 3 : Definition of heat measurement devices

Fluxmeter line	Position along the grain	Type of heat flux	Denomination
#1	1 (front)	Total	G1.T1
(plane of plume)	2		G1.T2
	3		G1.T3
	4 (rear)		G1.T4
# 2	1 (front)	Radiative	G2.R1
(between plumes)	2		G2.R2
	3		G2.R3
	4 (rear)		G2.R4
# 3	1 (front)	Total	G3.T1
(plane of plume)	2		G3.T2
	3		G3.T3
	4 (rear)		G3.T4
# 4	1 (front)	Radiative	G4.T1
(plane of plume)	2		G4.T2
	3		G4.T3
	4 (rear)		G4.T4

5.1.1 Inert test grain firing

Inert NMF firing test is an important step for the validation of the new test bench NMF and increase the maturity of the ignition modelling. Firstly, all the manufacturing process of the new grain is validated. The fluxmeters positions drilling is correctly tailored as well as the propellant inerting phase. Secondly, the firing test provided interesting measurements on the ballistics and heat fluxes. The ballistics exploitation of the firing is presented on Figure 10. The operating of the igniter is correctly modelled as well as the ballistics in the combustion chamber. For the igniter, the ballistics required to modify slightly the burning temperature to account for heat losses into the igniter. All the losses are reported on the gas temperature and the other igniter walls are considered with adiabatic conditions. For the combustion chamber, the inert propellant grain is modelled with heat losses thanks to its thermal characterization. The grain dissipates the energy coming from the igniter jets but does not ignite. This is the reason why the pressure into the combustion chamber does not increase as much as adiabatic boundary conditions will permit. As the chamber is completely sealed, the pressure upper limit is the one obtained at the end of igniter operating. As it can be seen on the picture, the pressure evolution of the simulation is much close to the one measured during the firing test.

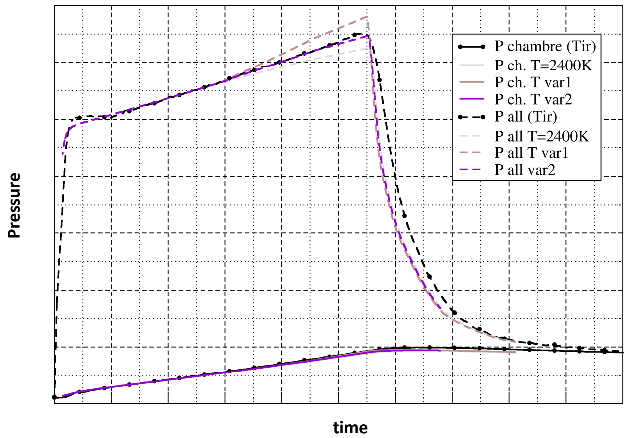

Figure 10 : Evolution of ballistics (combustion chamber and igniter) for the inert test firing

Another important goal of this firing was the use of the new fluxmeters specifically designed by Onera for ignition study. The Figure 11 shows a comparison of the measured heat fluxes and the simulated ones with the code Cedre. Total heat fluxes are considered here, i.e. they represent the addition of convective and radiative fluxes. Two locations are presented. The first one represents the positions of fluxmeters in line with an igniter plume. The total energy delivered is then coming directly from the jet. The second position is the one located between two plume planes.

As it can be seen for both locations, a very good agreement is observed although some discrepancies can be noticed for the second position (red lines). Whatever, the order of magnitude are correctly found by the simulations without other modification of the modeling. This shows that the radiation and the convection phenomena are well determined.

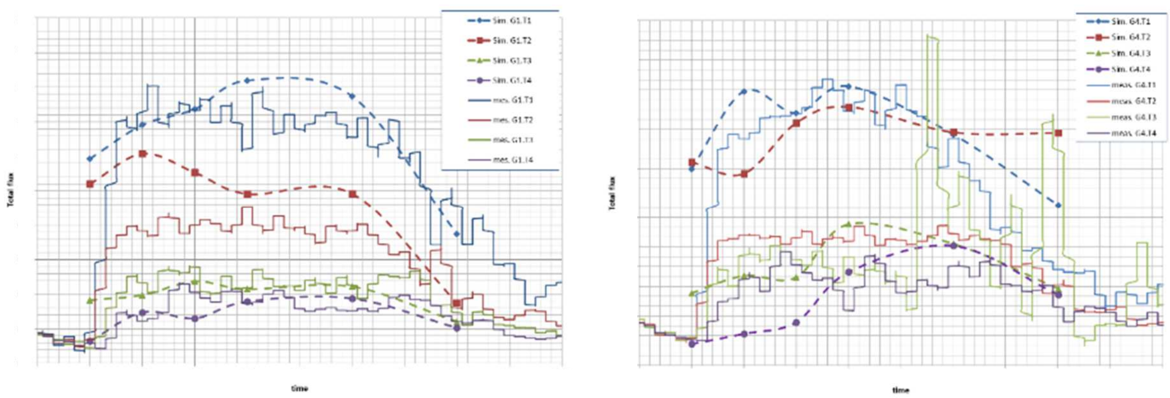

Figure 11 : Comparison of measured and simulated total heat fluxes
for both plans in igniter plume (left) and inter-plumes location (right).
The different curves correspond to the fluxmeter locations inside the test bomb.

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5.1.2 Al/AP/HTPB composite solid propellant solid firing

The grain was successfully fired on the 4th mars 2021 at the CRB research center. As for the inert test firing, the air inside the bomb has been replaced by nitrogen in order to prevent any reaction between the oxygen and the combustion gases. The bomb was equipped by 16 fluxmeters and two pressure transducers: one in the igniter and one in the combustion chamber. The next picture presents the test bomb before firing.

Figure 12 : NMF test motor before test

The nozzle is equipped with a seal that allows the pressure to increase up to 4MPa before being released. As the gases provided by the ignitor are not sufficient to reach such a level, the seal break-up guarantees the propellant grain is ignited. The next figure shows the plume at the mid-firing.

Figure 13 : NMF HTPB/AP/Al grain firing

The Figure 14 presents the ballistics in the igniter and in the combustion chamber where one can observe a classical pressure evolution. In a first stage, the pressure starts to slowly increase due to the injection of the gases provided by the igniter. After, an inflection on the pressure evolution can be noticed. It indicates the beginning of the grain ignition. An additional mass flow rate is added to the ignitor's one. A rapid increase follows that initial pneumatic phase until the break-up of the seal diaphragm. This is characterised by a sudden stop in the pressure increase before the pressure starts again to increase to reach its maximum a few millisecond later. As the igniter stops, the pressure slowly decreases to the stationary pressure once the total grain is ignited. The igniter pressure shows a sudden increase as the igniter events stop being shocked.

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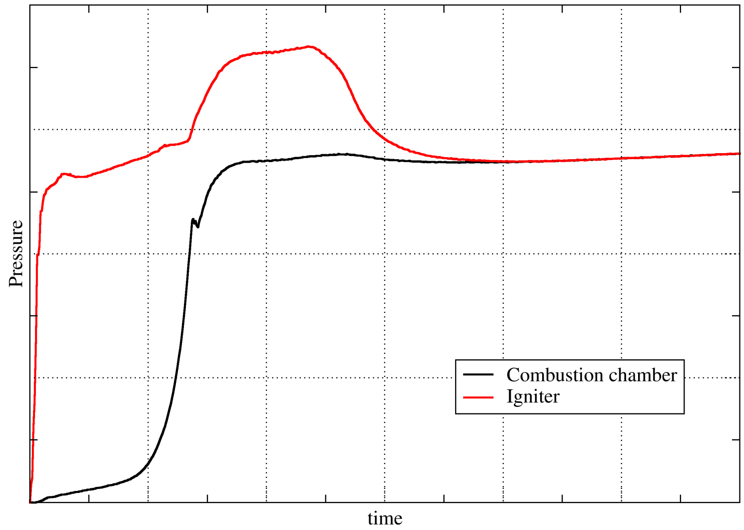

Figure 14 : Pressure evolution during the HTPB/AP/AL NMF firing

5.2 Exploitation of the MF firing test

The complete simulation of the firing is a complex task due to the number of physical phenomena involved. Some effects are especially important at small scale such as heat losses that may strongly influence the ballistics. In order to prepare the firing simulation, a preliminary calculation was performed to evaluate the thermal evolution of gas temperature as it was already done in [7]. A 10% decrease of the theoretical igniter gas temperature is applied to take into account of the heat losses into the igniter structure.

A simulation of the ignition of the NMF motor was carried out to demonstrate the capacity of the whole model to correctly reproduce the ballistics of the firing during ignition. A 3-dimensionnal domain is built considering the presence of the igniter. The mesh contains 210000 cells. The model “B” with the same set of parameters as in the previous calculations was applied to represent the propellant surface transient behaviour. As the combustion products contain an important amount of alumina, a specific treatment of this phase was added in the radiative heat flux. The condensed phase is convected as the gas phase. The radiative heat transfer is modelled by a Mie theory for the diffusion. A spectral model from Dombrowsky is also used for the definition of the particles optical factor.

A first simulation was carried out to test the numerical model built on the exploitation of flux/delay and flame spreading experiments. It is plotted on the red dashed line on the Figure 15. As it can be seen, a good agreement is obtained during the pneumatic phase before the grain starts igniting. Then a delay of a few milliseconds is noticed in the pressure increase even if the numerical slope is similar to the experimental one. At the end of ignition, the stationary pressure value is lower than the one experimentally measured showing something is missing to correctly predict the stationary ballistics. So, a second simulation was performed after having modified the combustion rate of the propellant in order to reach the stationary pressure. The obtained pressure evolution is plotted on the violet curve. The similarity with the experimental ballistic is much better, the seal break-up instant is correctly predicted. However, the starting of the pressure increase shows a less good agreement indicating that further work is still needed in the parameters set determination to better reproduce the experimental ballistics.

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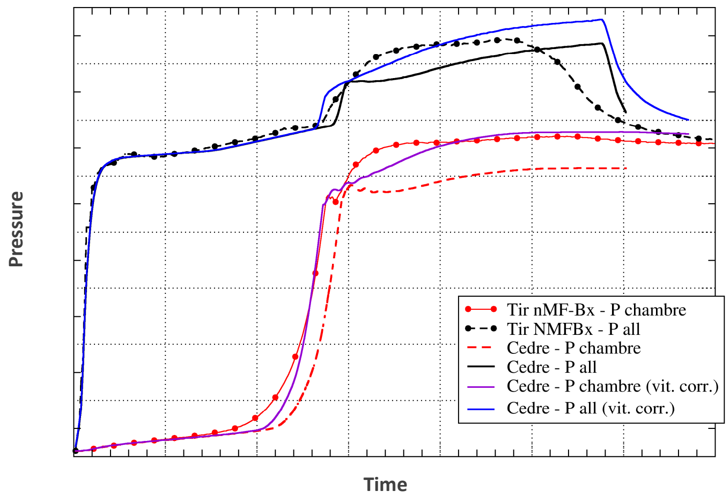

Figure 15 : 3D simulations of the NMF firing

The Figure 16 presents the concentration of HTPB/AP/AL propellant gas just after the grain ignition. The lines characterise the igniter gas concentration. The ignition starts where the igniter plumes impinge the grain surface. Note that at this moment, the seal diaphragm is still present and a vortex is created in the rear cavity. This vortex heats up the lateral face that ignites at last. When one compares the ballistics at that moment, it can be seen that the numerical simulation is too slow with regard to the experimental pressure. This point needs to be deeply studied. However, the model built on the basis of the exploitation of the experimental flux/delay and flame spreading velocity tests provides a good estimation of the grain ignition.

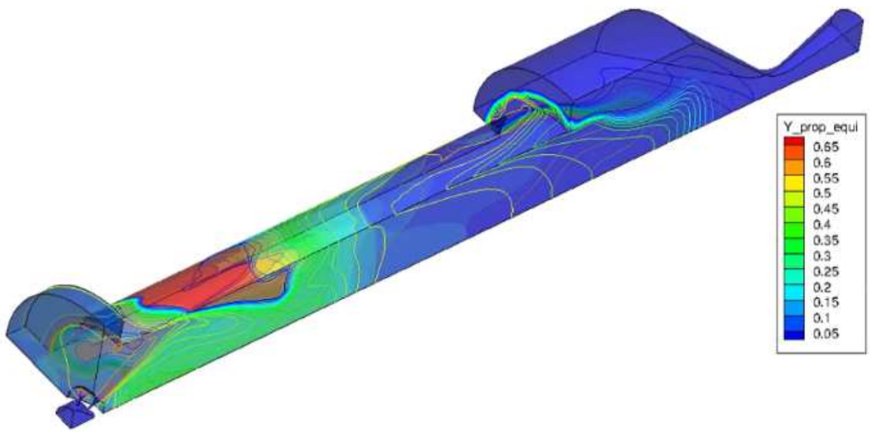

Figure 16 : Concentration propellant gas in the 3D simulation of the NMF firing at the grain ignition beginning (the lines represent the concentration of igniter gas)

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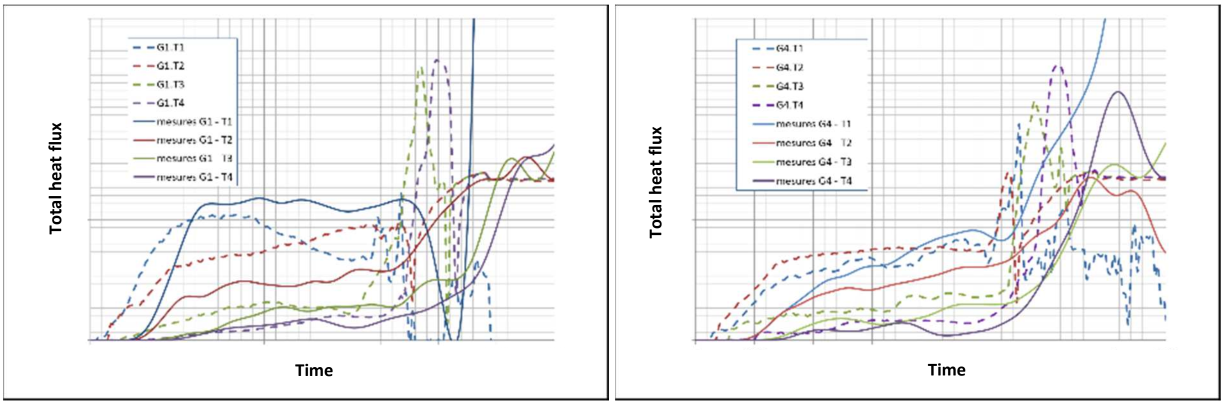

Figure 17 : Comparison of measured and simulated total heat fluxes
for both plans in igniter plume (left) and inter-plumes location (right)
The different curves correspond to the fluxmeter locations inside the test bomb.

Thanks to Onera manufactured fluxmeters, the total heat flux measurements are presented on Figure 17. A good agreement is globally obtained with the calculation results. The same order of magnitude can be found as well for the fluxmeter located in the igniter plume line as well as for the ones located in the line between two plumes. The comparison is more problematic with the second position (G1.T2 and G4.T2) for which the explanation is to be related to the 3D flow field and some perturbences at this location. Nevertheless, the evolution tendancies remains the same with a global increase of the values before the complete ignition of the grain.

The numerical simulation of the NMF firing test demonstrated the capability of the numerical chain, coupled with a dedicated ignition model (parameters determination required), to sucessfully investigate the physical phenomena involved in the ignition process.

6. Conclusion

This study presents the approach used in ArianeGroup to numerically investigate the ignition of SRM. It is based on both experimental and numerical tools. In a first step, a good knowledge of the propellant thermal properties is needed to access the resolution of the heat diffusion into the material. Secondly, the dependence of ignition delay with respect to a given flux allows calibrating the numerical ignition model “B”. The complete model is then applied to the simulation of the propellant flame spreading velocity. The good agreement obtained between the numerical and the experimental results provides a global validation of the model. At this stage, all the physical phenomena are addressed by the modelling. The model is applied to the calculation of the small scale Solid Rocket Motor. The firing of a HTPB/AP/AL composition grain is successfully simulated and allows the development of such an approach for the prediction and exploitation of the ignition of a full scale SRM.

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