TEMA : Thermo erosive behaviour of thermal insulators

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Abstract:

Enhancing solid rocket motor (SRM) performances beyond the already achieved levels requires an improved mastering of their environment. More precisely, one of the possible paths consists in reducing the inert weight to which the thermal insulator (TI) is a main contributor. Keeping this goal in mind, an accurate modelling of the thermo erosive behaviour of TI will warranty the capability to limit these to their minimal thickness. With this objective, Snecma Propulsion Solide (SPS) requested SNPE Matériaux Energétiques (SME) in order to develop a specific experimental setup able to characterize these materials behaviour, exposed to hot gases, in functioning conditions that would representative of full scale SRM.

This paper shows the method and the important steps of TEMA setup development from the first specifications up to the firing test campaigns and the method of determination of erosive law on new materials.

INTRODUCTION

Enhancing SRM performances beyond the already achieved levels requires an improved mastering of their environment. More precisely, one of the possible paths consists in reducing the inert weight to which the TI is a main contributor. Keeping this goal in mind, an accurate modelling of the thermo erosive behaviour of TI will warranty the capability to limit these to their minimal thickness. With this objective, Snecma Propulsion Solide (SPS) requested SNPE Matériaux Energétiques (SME) in order to develop a specific experimental setup able to characterize these materials behaviour, exposed to hot gases, in functioning conditions that would representative of full scale SRM.

On the basis of aero thermal calculations, SPS specified the principle and fixed the dimensions of a chamber in which the internal thermal insulator (ITI) sample is exposed to the tangential flow of hot gases provided by the combustion of a solid propellant grain. In order to meet the requirements, among which being representative towards the full scale motor is essential, the TEMA set up, as developed by SME, includes a grain shape which is quite unusual in propulsion. Choosing this architecture and taking benefit from its capability to be adjusted both in terms of shape and dimensions, TEMA allows a broad range of loadings to be explored, for all different states of SRM functioning.

This paper shows the method and the important steps of TEMA setup development from the first specifications up to the firing test campaigns and the method of determination of erosive law on new materials.

SPECIFICATIONS

For referenced materials, experimental data available with full firing tests exists and allows the validation of erosive laws for the design of Internal Thermal Insulation used in Solid Rocket Motor. For new materials development, the model available for thermal erosion calculation is not usable since it is based on an erosion criterion defined on a specific material. Consequently, for each new material, it is necessary to perform one or more tests (in different configurations) at full scale in order to determine a specific erosion criterion. As a result, there exists a real need to enable tests to be performed at lower cost, which means a subscale test, thus making it possible to avoid any need to perform test firings at full scale.

Existing reduced scale test means in use for thermal erosion behavior characterization of ITI are based on cylindrical extenders of small diameters. Inspecting those tests showed that the aspects of degraded material and erosion levels observed during such tests are rather different from those observed on full-scale motors. Thus, this kind of test allows a comparison of thermal and erosive behaviors between different TI materials but is not representative of full-scale aerothermal loadings.
As a result, Snecma Propulsion Solide has worked on the project of a specific subscale setup which main characteristic would be its full-scale aerothermal environment representativeness.

The performance of thermal protection is evaluated in terms of thermal erosion behaviour in response to the hot gases generated by the combustion of propellant. This mechanism occurs in two phases. First, under the effect of the high temperature, the internal thermal rubber insulator becomes degraded on the surface by forming “char”. Then, this degraded material is subjected to erosion with greater or lesser extent as a function of its exposure degree to the flow and as well of flow velocity.

The figure 1 shows the different characteristic thicknesses for ITI material needed for thermo erosive behaviour evaluation.

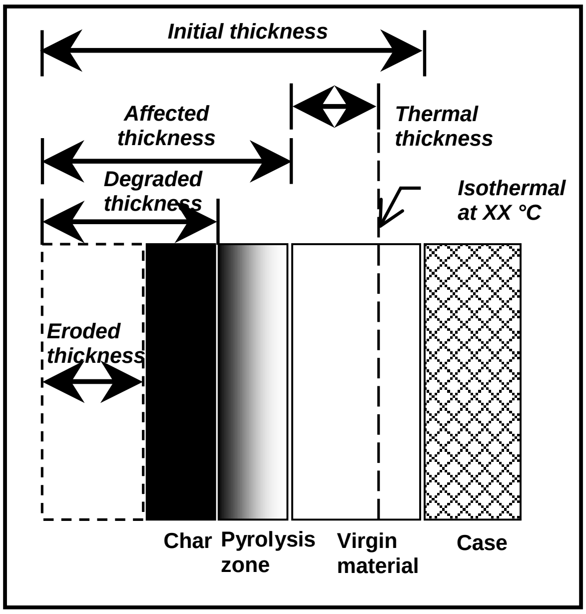

Fig. 1: characteristic thickness of ITI degradation

Being representative of full-scale motor is the principle requirement of this set-up. Indeed, numerical studies were conducted in order to precise the subscale test design. The principle aims of design simulations are summarized below :

- Checking aerothermal solicitation levels on the material evaluated in order to cover a range of loadings representative of a full scale SRM
- Defining suitable pressures levels to cover all the operating conditions during SRM functioning

Besides, with the objective of aerothermal loadings control :

- Avoiding alumina particles impact on material sample (see calculation fig. 2)
- Avoiding the effect of aluminum combustion on the radiative solicitations on the TI material sample

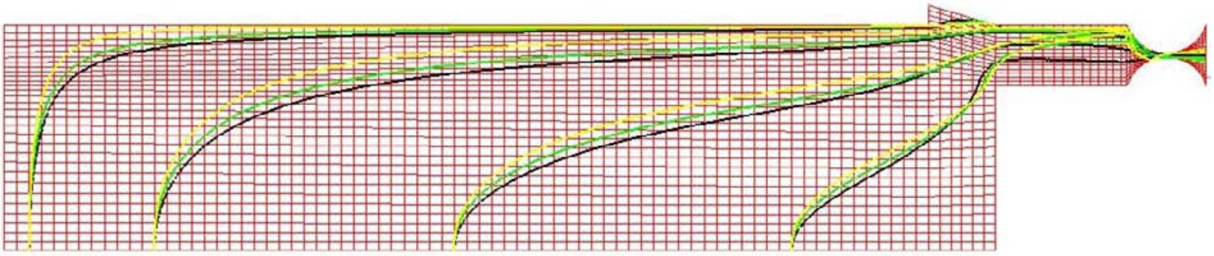

Fig. 2: trajectory calculation for different sizes of alumina particles

As a result, these calculations led to the following definition of the TEMA setup:

- Parallelepiped shaped test chamber with a plane material sample
- Four pressure levels defined to cover all the operating conditions during SRM functioning
- Burning surface remaining constant, which means chamber pressure remaining constant
- Adjustment of material sample length in order to cover a wide range of aerothermal loadings representative of a full scale SRM :
    - In the first half of the plate, beside the front end wall, stresses are typical of the cylindrical part of the structure as well as the front end wall zones of SRM
    - In the second half of the plate, beside the nozzle, stresses are typical of the rear end of SRM in a deflected configuration
- Adjustment of test chamber height and choice of suitable propellant :
    - To keep the same range of loadings, heat flux and flow rate, in all firing tests with different pressure levels
    - To avoid alumina effects on material sample

Furthermore, TEMA setup must cover all of the erosion conditions that an ITI material can encounter in solid propellant rocket motors like an EPDM polymer loaded with silica. Three different regimes can be distinguished:

- non-erosive or conductive thermal conditions : stresses are only thermal and the char layer that is formed remains in place
- Pulsed erosion conditions : an intermediate regime where the layers of char of a thin thickness are ejected one by one in the form of plates
- intensive erosive conditions : the char layer is ejected as soon as created under the effect of extreme flow severity.

The choice of a plane material sample allows a better representativity of full-scale loadings based on the fact that curvature radii are large in full-scale SRM.

TEMA SETUP

TEMA major characteristics

Keeping in mind these specifications, and the principle that had been specified by SPS, an original setup, TEMA has been designed and manufactured by SME teams.

TEMA can be described as a plate of thermal protection material, being exposed to a tangential flow of hot gases generated by the combustion process of a solid propellant block, facing this sample. One of the major characteristic of this setup is its propellant grain, with a parallepipedic shape, quite unusual, in propulsion field. Then, to meet the requirements on aluminium effects, a classical HTPB based composition was chosen with AP and Al charges.

The test device also includes means for adjusting the distance between the propellant grain and the plate of thermal protection material under test. In this way, aerothermal stresses levels within the device can be set by adjusting the height of the combustion chamber, thus making it possible to keep a level of stress that would be similar from one firing test under specific conditions, to another. Indeed, operating pressure can directly be adjusted by means of the diameter of the nozzle throat.

One has understood that the TEMA principle is a parallepipedic system. Keeping a purely rectangular shape would require metal- plate of great dimensions and weight, for pressure levels withstanding. That is why it was finally chosen to have a final setup with cylinder shape, enabling pressure forces to be uniformly distributed. Indeed, after assembly, the operating system (constituted of the thermal protection plate, combustion chamber and the propellant grain) is put in the inside volume of a dedicated cylindrical shell, then placed in a case constituted of a metal tube of reasonable thickness. Both front and rear ends are closed with metal plates, with nozzle at rear end.

To end with this TEMA setup brief description, one has to note that the propellant grain is inhibited on all faces except the one facing the TI sample, for constant burning surface during combustion.

As described in the previous section (specification), dimensions of the plate were fixed with preliminary aerothermal calculations, (1/1 scale representativeness). TEMA setup length is around one meter, with 0,6m external diameter and the propellant block weighs roughly 50 kg, for 15 to 30 sec of firing test (depending on the pressure level). A cut view of TEMA device is given in next figure.

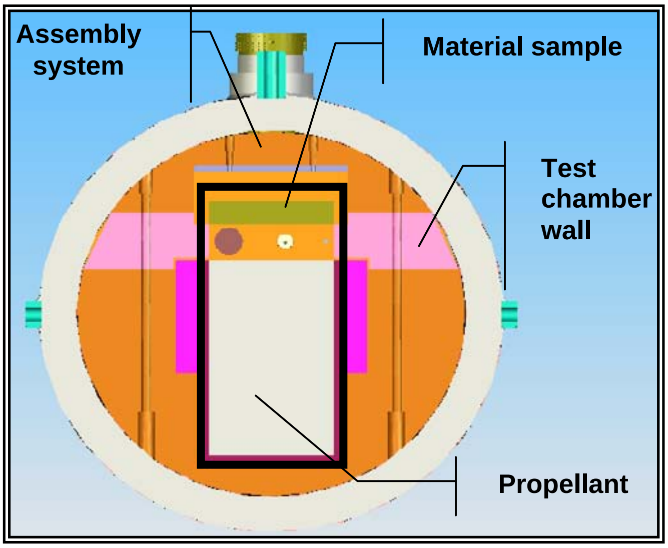

Fig. 3: TEMA setup cut view

In such a setup, the combustion chamber is comprised between the plate of material under test and the burning surface of the propellant grain. This configuration induces different levels of stress on the exposed face of the plate, since the flow of hot gases is greater and faster when getting closer to the ejection nozzle. We insist on the fact that this characteristic is one of the most important on this device: it is thus possible in one firing test, to have different stress zones, at different locations distributed all along the sample length. They are directly representative of certain portions of the 1/1 scale states of SRM functioning.

Back to TEMA primary objectives, it seems obvious that this device has to provide accurate data for ITI material characterization. Indeed, numerous instrumentation was defined.

Instrumentation

TEMA setup includes means for measuring degradation evolution, coupled with TI material regression rate.
Indeed, the material plate sample includes sixteen thermocouples, distributed in various positions along the plate and at a determinate depth in its thickness. These temperature measurements are necessary for thermal characteristics validation of the tested material.
Furthermore, four ultrasound transducers are used to study the pyrolysis zone evolution as well as the affected thickness modification during combustion. The figure 4 shows the principle of ultrasound measurement method.

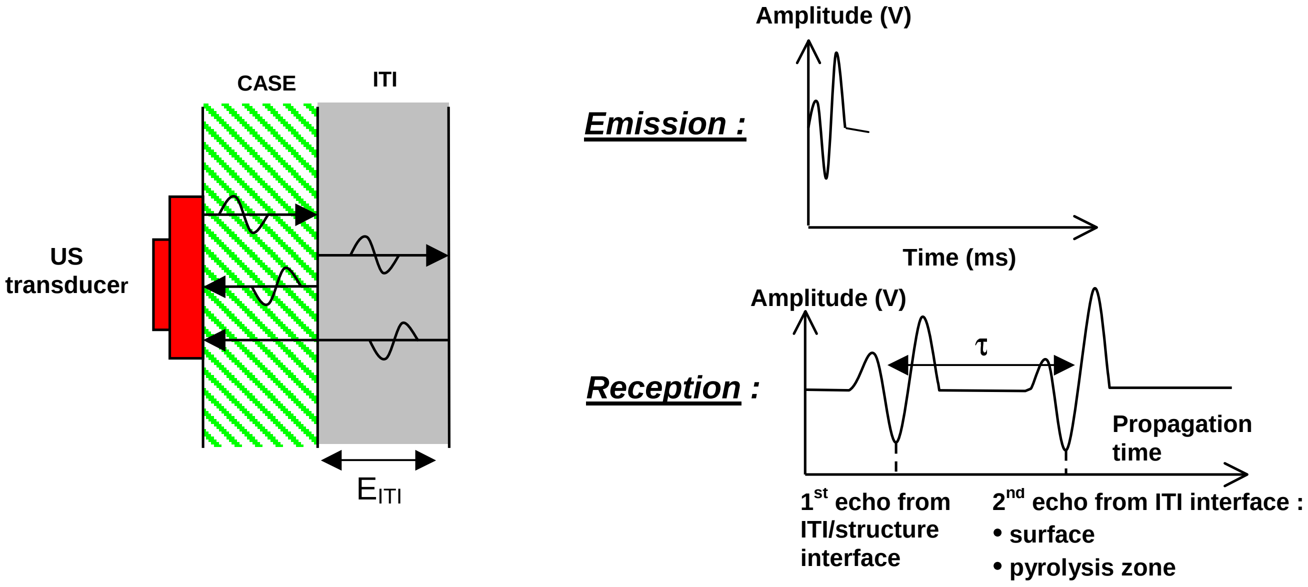

Fig. 4: principle of ultrasound measurement

The principle of this method is well – known: it is similar to the sonar technique [2]. An ultrasound transducer emits mechanical waves that travel through the tested materials or the stack composed of different materials, structure and ITI (SRM firing test) for instance. They reflect on each acoustical discontinuity (surface or any other interface like pyrolysis zone) and the transducer detects the different returning signals. The precise measurement of this mechanical wave propagation time is directly related to the material thickness via the mechanical wave velocities. In TEMA setup, the US transducers are located along the case of the solid rocket motor.

The ultrasonic method is based on the variation of the propagation time of the emitted and reflected ultrasonic waves through the tested material. However, some events can affect this time interval:

1. the ITI thickness variation (virgin material, pyrolysis zone and char) due to ablation phenomena;
2. the precise location of the reflection surface. For virgin material, its position is well known, at wall, but as soon as decomposition occurs, its position is somewhere in the pyrolysis zone (porosity limit) ;
3. the local ultrasonic wave velocity. It depends on the thermal profile and the stress-strain distribution (essentially inner pressure) within the tested material. When temperature rises up, wave velocity decreases, leading a propagation time increase.

Sometimes it can be very difficult to deduce the propagation time variation from the analysis of the ultrasonic signal evolution. Indeed, the different echoes detected can completely change during tests (in terms of amplitude, for instance), or even disappear. That is why the continuous representation of the propagation time variation obtained from this analysis has always to be confronted with physical considerations.

In the next chapter, details of ultrasound measurement method used to study the degradation process of ITI in the part about data analysis are given.

The last technique that is used to characterize ITI materials behaviour is the plasma capacitance gages (PCG): with a number of four sensors are used in TEMA set-up. This technique was developed in the United States during the 1980's at TWR and in France at ONERA in the 1990's [1], mostly to measure internal insulator erosion. This method is based on the electrical capacity variation with time between two electrodes which is directly related to the material thickness. The first electrode (the sensor) is located along the outside surface of material sample and the plasma generated by the combustion gases forms the second "fictitious" electrode. The capacitance increases as the thickness of insulator decreases and these data yield real time information on insulation thickness and behaviour. The relationship between the thickness and the output voltage is not linear. A pre-test calibration is required on various tested material sample of different heights. As a result, the PCG technique gives the erosive rate of ITI material during firing test.

Indeed, for the TEMA application, ultrasound measurement and plasma capacitance gage are complementary, for material thickness evaluation during combustion.

At last, pressure transducers complete instrumentation on TEMA setup. They are used for classical pressure control in combustion chamber all along the firing test.

Firing test preparation

The early implementation of this numerous and even fragile instrumentation was a manufacturing challenge. Thus, preparation steps, quite similar to those in propulsion testing were defined. This includes specific molds manufacturing. Indeed, the propellant grain is full molded, after curing. Its inhibiting process includes reinforcement plates, in areas where hot gases are more aggressive, or in angles zones, where bonding stresses can be quite strong.
The other major step in TEMA test preparation concerns TI sample preparation, central part of this device and method. It begins with thermocouples implementation as soon as the thermal insulator plate is manufactured.
Then, the four PCG are glued on this plate, regularly placed from aft end to rear end. Finally, this instrumented plate is inhibited on all its face except the one facing hit gases in combustion chamber, so that sensors will be protected. Indeed, all instrument wires come out at front end.
Final assembly between TI material, with in-core sensors to be evaluated, up and back half shelves (for a cylinder shape) and chamber walls, which main objective is to ensure combustion chamber integrity, is made with rods (no bonding). Holes have also been made in the shells so that the whole device is well pressurized, as soon as the propellant is ignited. Last step is to put this entire system in the test case, followed by both ends closures. The next figure gives an overview of TEMA assembly and setup.

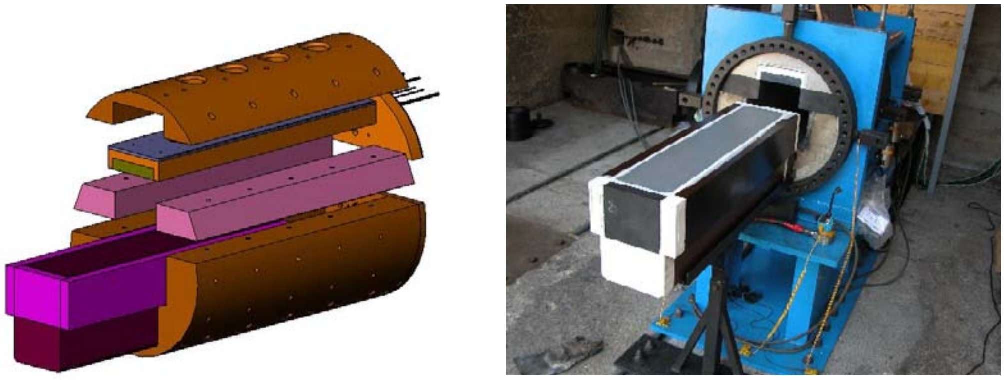

Fig. 5: TEMA assembly and device overview

Firing test and results

In regards to those complex preparation steps, firing test is quite simple and, can nearly be compared to a classical propulsion test, with a constant pressure curve. Pictures taken during one of the first series of firing tests are shown on next figure.

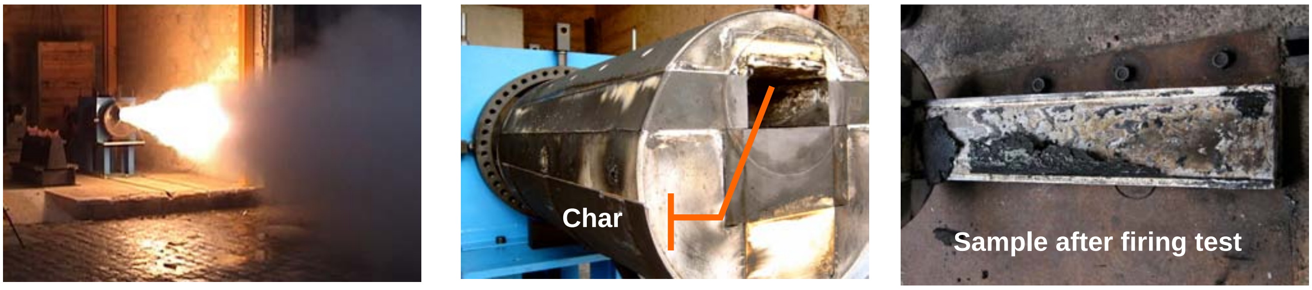

Fig. 6: TEMA firing tests and expertise

After dismantling, ITI material sample is carefully analyzed, in terms of thickness, aspect, especially in rear area, where char portions can be observed, and recovered. Then, thickness measurements are made after scraping off, and compared to those on virgin material before testing

Right after test, a first analysis of data is made, after their conversion in physical units (thanks to preliminary calibration): correlation between temperatures and thickness signals and their position in TI plate is studied. Further exploitation is then made on all these data.

DATA ANALYSIS

With the database of measurements obtained with TEMA trials, SPS has developed a specific data analysis method to determine an erosive law to be applied on ITI materials that have been tested. The following figure gives an overview of this exploitation methodology principle.

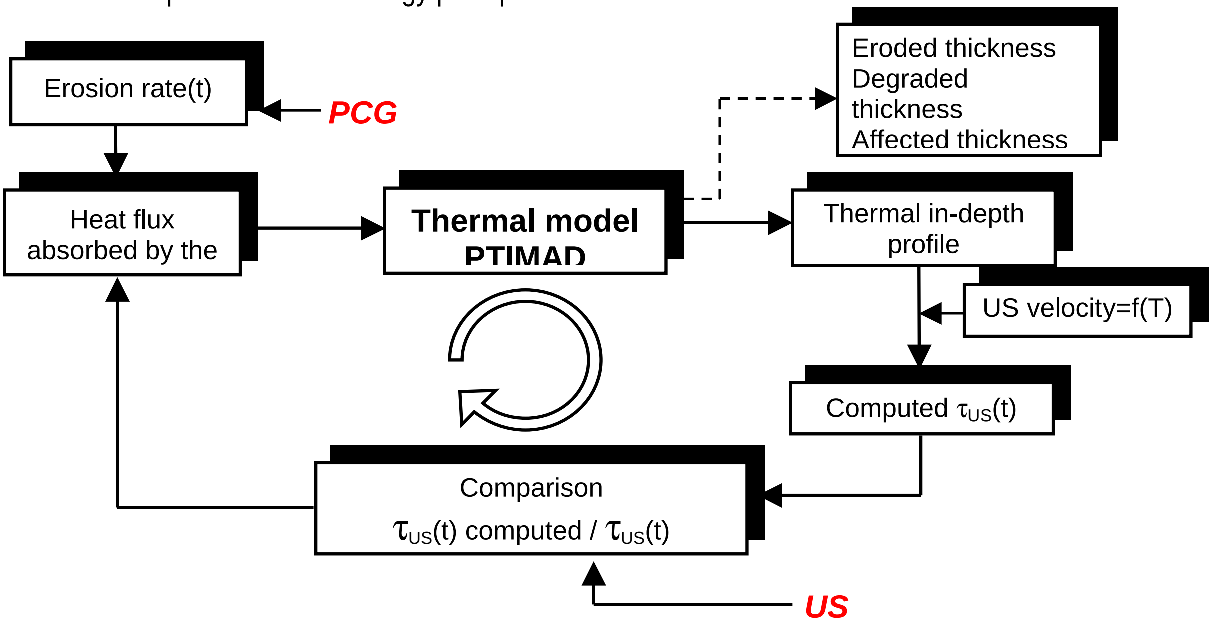

Fig. 7: Methodology of data analysis

The ITI material studied here is a silica filled EPDM rubber, on which a series a tests have been performed with TEMA setup during validation phase. Under high temperature, in-depth decomposition of this material leads to the formation of a porous and brittle char residue. For accurate prediction of such material behaviour, the thermo-ablative code PTIMAD was developed at ONERA and SPS requires a lot of different physical characteristics (thermal conductivity, specific heat, weight loss kinetics,...).

Whatever type of information is researched (thermal properties or thermal fluxes), the ultrasonic method has to be coupled with inverse identification method based on the PTIMAD code.

With this method of exploitation, the measurements acquired during series of TEMA trials on ITI samples with such instrumentation can be used for accurate characterizing of ITI material thermo-erosive behaviour. Moreover, one test on one ITI sample, will give information for a range of stress, and pressure level. Indeed,, after test, and data analysis conditions for subsequent tests on same ITI material can be precisely defined by stress levels adjustment. Finally, calculation methods can be rather improved, and erosive law for thermal protection is obtained and then used for accurate design at full scale.

Thermocouples

Exploitation of thermocouples is made with the thermo-ablative PTIMAD code. This thermal analysis allows eliminating incertainties due to the aerothermal stresses calculations. Indeed, thermal measurement of the first thermocouple close to the exposed surface is imposed during calculation process as boundary condition. The comparison between computed temperatures and measured signals from thermocouples put more deeply allows the validation of thermal behaviour and characteristics used in thermo-ablative code.

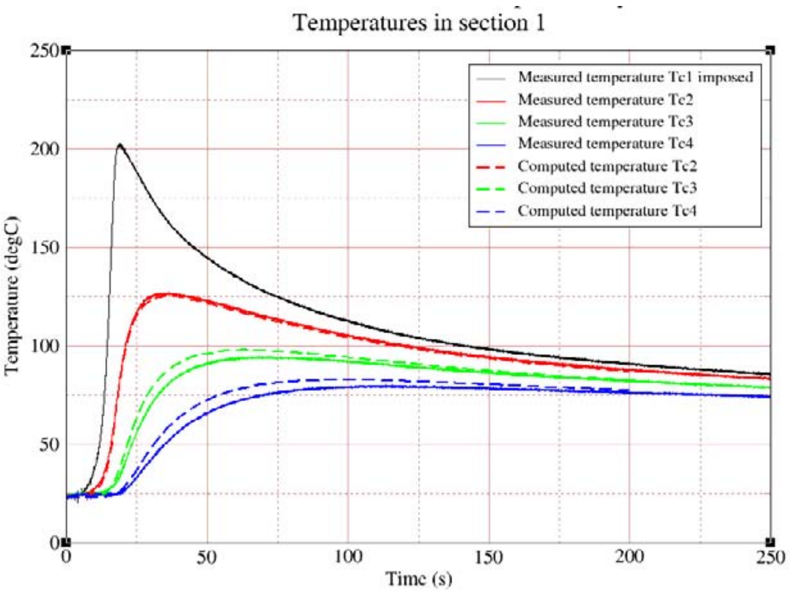

Fig. 8: example of thermocouples exploitation

Plasma Capacitance Gage

The PCG technique is theoretically used for surface evolution study of material sample during firing test. As a result, the PCG gives the erosion level function of time. However, this technique used on its own can not give an erosive law accurately. Indeed, the understanding of the PCG behaviour is dependant on the plasma precise location, near the ITI surface in the boundary layer. This boundary layer is subject to variations along the material sample depending on erosive conditions during the firing test. As a result, we must perform a global exploitation of the PGC signals and ultrasound measurements that are localised in same sections to determinate erosive laws and pyrolysis behaviour of ITI materials tested.

Nevertheless, before complete exploitation, PCG allows to obtain important informations about erosive behaviour. The following figure shows thickness evolution given by PGC for two firing test performed at a same combustion pressure and with two different materials. This comparison is made for the same measurement position (section) for both sensors.

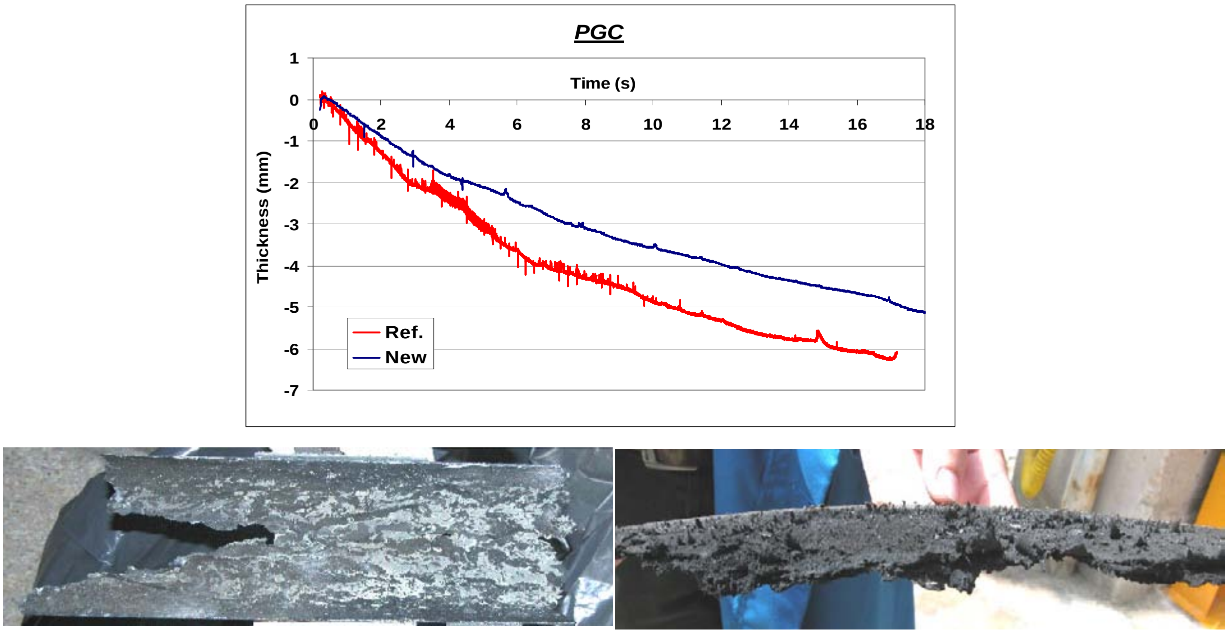

Fig. 9: PCG comparison and chars aspects between two ITI materials

The erosive rate is higher for the reference material and the new material seems to be more resistant.
When we compare the two chars after firing test, the char of the new material is stronger and thicker than for the reference material.
Another example of analysis is the comparison of signals given by PCG for the same firing test but at two opposite section. Close to the nozzle, PCG give a regular curve without spike that would be characteristic of a regime when the char layers are ejected as soon as they are created under the effect of high speed flow.
On the opposite side, the spikes on PCG trace correspond to the ejection of a part of the char layer during the intermediate regime of pulsed erosive conditions.
As a result, a visual confirmation of such a diagnostic is given by the next remark: with the char after firing test and the knowledge of erosive conditions on the material sample, of PCG analysis.

Ultrasound measurements and PCG analysis

The joint analysis of US signals, PCG and thickness measurements after test are then used for the erosive law determination with flow parameters.

The PTIMAD code was modified by adding a specific subroutine devoted to the ultrasonic wave propagation. It integrates the propagation time all along the thermal in-depth profile. Indeed, the wave velocity as a function of temperature is a new data of the PTIMAD code. ONERA has experimentally measured the evolution of the ultrasonic velocity up to a high level of temperature that is representative of the start of the material degradation under quasi-steady conditions. Above this temperature, the ultrasonic velocity has to be extrapolated.
Whatever information we are seeking (thermal properties or thermal fluxes), the ultrasonic method has to be coupled with inverse identification method based on the PTIMAD code.

The figure 9 displays an example of curves of US and PCG analysis for the same firing test at two opposite positions: head end and aft-end near the nozzle.

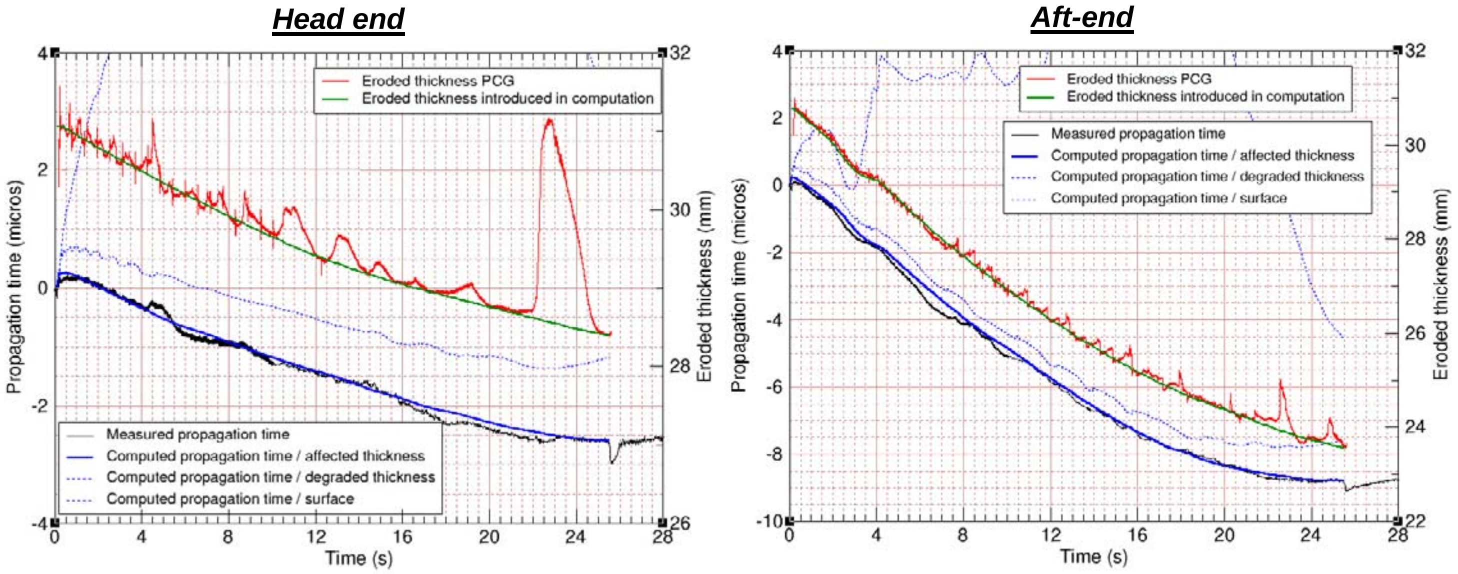

Fig. 10: PCG comparison and chars aspects between two ITI materials

The degradation process was observed either by PCG and by ultrasound transducers as sensors for both techniques were placed at same positions in material length. As discussed in the ultrasound technique presentation, the heat from hot gases coming into the material modifies the variation of the propagation time of the ultrasound waves. Ultrasound measurement is related to the pyrolysis process inside the solid phase. In figure 8, the char behaviour can be observed for two sections: the spikes on PCG trace for the head end measurement correspond to the ejection of portions of the char layer whereas, for the aft-end measurement, the regular trace without important spikes shows a stronger erosive rate with a char layer that is eliminated as soon as it is created. The ultrasound trace shows slope variations attributed to heat transfer balance that occur at the same time as a char layer is ejected. The insulator degradation process could be studied in details and improved using both

techniques: PCG is helpful for the study of the core flow effect on the char and ultrasound measurements indicate the heat flux history according to analysis described in the figure 5. More precisely, with the erosion rate obtained by PCG, the identification method with PTIMAD gives the heat flux that is absorbed in the ITI all along firing test.
The final validation of thermo-erosive calculations and erosive law is based on comparison between affected thickness, one being measured and the other as a result of calculation, obtained as described in the previous section.

CONCLUSIONS

A first series of firing tests has been conducted to characterize the pyrolysis zone and eroded thickness on a referenced and well characterized material, which confirmed the capability of this device to match well the requirements. Based on the obtained data, the derived erosion law could be compared to available full-scale motors experience and proved to be confident. Once, the TEMA setup capability has been proved, further firing tests have been performed with success on new TI materials, for a complete characterization and in order to determine their erosive laws by Snecma Propulsion Solide.

A considerable promise is given by TEMA setup in advanced thermal protective material characterization for propulsion applications. Nowadays, applications concern mostly ITI rubber materials but TEMA could be extended to any other types of thermal insulator like, for example, ablative phenolics and C/C composites.
Furthermore, TEMA setup have important abilities for a better understanding of aerothermal and radiative flux especially with ultrasound measurements and PCG analysis.

ACKNOWLEDGEMENTS

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A French patent was filed in 2006, with European and US extension.
This work is the result of a successful technical cooperation, well managed between teams of Snecma Propulsion Solide and SNPE Matériaux Energétiques.

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