Modelling of Classical and ETC Manometric Closed Vessel Tests

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ABSTRACT

In the scheme of the French ETC Programme, we study the modelling of ignition and combustion of propelling charges and of their effects. In this paper, we evocate the evolution of the research performed. We analyse 460 cm3 manometric closed vessel test results to estimate combustion rates of several single base gun propellants, energy losses to the bomb wall and their possible models. The state of the theoretical background for models is presented. The experimental results are obtained with classic hot wire ignition and 20, 30 and 40 kJ plasma ignition. The analysis of these results shows less significant enhancement of apparent combustion rate than for double base propellant results we presented at 19th ISB. We are developing an elementary global code which simulates these manometric closed vessel tests. This model takes into account the total volume itself and not yet the plasma torch and the vessel. The models tested for energetic flux are based on simple physical principles as presented and applied to one classical single base propellant shot where the best fit with the experimental data is sought.

RESUME

Dans le cadre du Programme ETC Français, nous étudions la modélisation de l'allumage et de la combustion des poudres propulsives et de leurs effets. Dans cette communication, nous rappelons l'évolution de la recherche effectuée. Nous analysons des résultats de tirs dans une bombe manométriques de 460 cm3 pour estimer les vitesses de combustion de plusieurs poudres propulsives simple base, les pertes énergétiques aux parois de la bombe et leurs modèles représentatifs possibles. L'état des bases théoriques des modèles est présenté. Les résultats expérimentaux sont obtenus avec un allumage classique à fil chaud et par allumage plasma de 20, 30 et 40 kJ. L'analyse de ces résultats moins d'augmentation significative de vitesse de combustion apparente que ceux présentés au 19th ISB pour une poudre propulsive double base. Nous développons un code global élémentaire qui simule ces essais en bombe manométrique. Ce modèle prend en compte le volume total de l'enceinte et pas encore la torche à plasma et l'enceinte. Nous présentons des modèles testés pour les flux énergétiques qui sont basé sur des principes physiques simples et appliqués à un résultat de tir classique d'une poudre propulsive simple base où le meilleur accord avec les résultats expérimentaux est recherché.

INTRODUCTION

Two decades ago, the French Ballistics Programme started to study classical ignition, interior, intermediate and external ballistics. This programme associated French universities, research centres and industrials. A part of this programme was the modelling of the phenomena involved starting from the fundamental, applied research, technologic and experimental states of the art described in existing references works as, for instance, Krier et al [1]. In these references, the physical models usable for modelling and their limitations were discussed. In this scope, models 1) for interaction of the gas phase (ignition flame or combustion products) with the surfaces in contact (gun propellant grain and wall of he vessel) 2) for dynamic problems (fluid, projectiles,..) were investigated. The methodology followed consisted in coupling experimental and theoretical works to achieve computer codes fitting well enough with experimental data issued from the proving ground or the battlefield. These works consisted in building computers codes calibrated first with limited experiments, then validated with more experiments up to eventually battlefield experience. The physical models in the computer codes may have to be improve by successive approximation if the deviation of numerical simulation with experimental data is not good enough.

Classic ignition Computer Fluid Dynamics (CFD) modelling

CFD computer codes were developed generally 1-D, then 2-D and then sometimes 3-D.
For interior ballistics (IB) of large calibre guns, these codes used for :

- ignition : zones already ignited of the propelling charge or not and classical radiative, conductive, convective expression for ignition of the propellant grain,
- combustion : the classical expression of combustion rate r of the gun propellant depending on pressure of the gas phase Pg,

CRB, ISL and EFAB developed CFD interior ballistics computer codes 1-D, then 2-D axi-symetrical, respectively MOBIDIC, AMI and CAPA codes. These codes were compared during workshops on experimental configuration. As it was checked, once the ignition phase ceases, the model maybe be quickly degraded to 1-D for the projectile movement. The state of the art of CFD modelling and computers showed a very far term possible for 3-D modelling of IB.
But the 3-D modelling seemed to us essential to have at least a more fundamental knowledge of the ignition phase of the propelling charge. In case of a technological apparent impossibility, it would have been possible :

- 1) to test by numerical simulation the other possible technological solutions without experimentation,
- 2) to select the calculated best ones,
- 3) to evaluate them experimentally to know the technologically best ones and eventually to calibrate and validate the models used.

But no technological impossibility appeared, the old centre core igniting system or igniter generating its ignition flame on the first half of its length was replaced satisfactorily by a new one generating its flame on its whole length, as remembered in the next paragraph.

The second thesis of Porterie [2] describes the achievement of CAPA-2D applied to the modelling of the ignition phase of a 105 mm gun. A part of the calibration was done with experimental results including techniques of high speed photographic and processing of data :

- for 3-D output of igniting systems [3] to estimate the ignition function (masse and energy fluxes) coming out of the vent hole(s) of the igniters as data input of their model in open air,
- for translucent or transparent ignition simulator to observe luminous phenomena related

to pressure waves, pressures evolution and the flame propagation in the propelling charge up to 100 MPa.
In this work, four numerical simulations are performed : the two first correspond to the calibration with the two large calibre igniters of [3] mentioned in the previous paragraph, the third one with an igniter generating its flame on the last half of its length and the fourth one with a simple numerical breakage model increasing by 20 % the surface of the propellant grain when its estimated compaction limit is reached. This last simulation showed an unwanted pressure rise.

Classic ignition 0-D modelling

0-D (or global or lumped parameters) codes considering original ablative (compared to Vieille's law) models of gun propellant ignition or combustion rate taking into account the composition of the combustion gas phase and the associated energetic feedback to the surface of the propellant were developed [4,5] and used for other applications [6,7].

ELECTROTHERMAL CHEMICAL (ETC) IGNITION AND COMBUSTION

The arrival of ET launcher and then ETC launcher (plasma ignition or combustion of energetic materials) restarted this interest in modelling and associated experimentation and launched the corresponding French ET, then ETC Programme. The ET launcher was studied and modelled by ISL, CEA and GI. A 0-D code was developed for ET launcher [8,9] coupling limited (12 chemical species for CHO) thermodynamic equilibrium calculations with internal ballistics and ablative models for liner of the plasma torch and for the working fluid. A wider (100 chemical species for CHON) thermodynamic equilibrium code for plasma was presented at 9th EML [10]. These works showed the interest of coupling of the calculation of thermodynamic equilibrium calculations with 0-D modelling and with experimental data for calibration and validation purposes. In the scope of French ETC Programme, several plasma igniters are developed [11] and evaluated. The final objective of 0-D modelling is to get a easy to use 0-D code, leading to a n-D code when necessary. The research way chosen was to evaluate physical or chemical models first with constant volume closed vessel with a plasma torch, then with a variable (by projectile movement) volume one with a plasma igniter.
We presented several points of this on going research at 19th ISB [12]

Combustion rate of gun propellant

The different models of the international literature based of physical or chemical effects which impose their burning rates upon the global combustion model were 0-D evaluated on experimental data obtained with a double base propellant. These models were :

- ablative by energetic transfer to the surface of the propellant ;
- essentially radiative coupled with other physical models :
    - with an ablative model ;
    - with solid phase reaction kinetics in the surface layer of the propellant ;
    - with modification of the propellant in the vicinity of the burning surface ;
- different combustions of parts of the propelling charge plasma when ETC ignited;
- semi-empirical pressure P models including :
    - the temperature of the gas phase ;

- the electrical power injected into the propelling charge.

All these models, some of them with an enhancement of intrinsic combustion rate under ETC or not, showed a good fitting with experimental data.

So, it appears in this case that several different causes may have the same effect. The problem is to find out a realistic partition of the causes, or the main cause, which explains the effect.

Energetic fluxes

The particular point of energetic flux related to ablative model of combustion rate and to energetic transfer to the wall of the vessel was discussed, too. The STANAG 4115 method assumptions used to estimate the energetic flux to the wall showed a reduction of the flux after the point of inflexion of the pressure rise in the closed vessel. This fact is puzzling, as in first analysis, we suppose it depends on the pressure of the gas phase and the temperature of the gas phase and of the surface of the wall. CRB [13] works on atmospheric or low pressure spectroscopic measurements shows out-of equilibrium particles in the reaction zone of burning propellant generated by gas phase kinetic reactions in this area. At ambient pressure, the reaction zone is some cm thick ; at high pressure its thickness is known to tend toward zero. The reaction zone is similar to boundary or vapour layer and corresponds to the interface between the surface of a solid phase and a gas phase in local thermodynamic equilibrium state. As suggested by Oberle et al. [14], for some propellant whose combustion rate is enhanced at low pressure by plasma compared to classical combustion rate becomes identical at higher pressure, the vapour layer (combustion reaction zone) permeable to plasma influence at low pressure becomes an opaque layer at higher pressure. The plasma influence may be material and or radiative and depending of the structure of the reaction zone : according to the pressure, a portion of the zone in contact with the surface of the propellant may be sufficient to stop the plasma influence and let the energetic feedback the same as classic one.

A way to solve the problem of estimating the energetic fluxes and transfers from the gas phases to the surfaces, and the associated ablation problems, was to calculate the local thermodynamic equilibrium (LTE) properties and transport coefficients of the gas phase(s) and research relations with the experimental data.

Coupling of LTE with experimental data

We presented coupling of LTE with experimental data to estimate the transient temperature of the gas phase for the double base propellant we studied. It was achieved by interpolation with EXCEL of tabulated values of thermodynamic properties at several fractions of plasma injected or propellant burnt.

Calculation of transport coefficients

A background of plasma works [15,16] on modelling and experiments on microtorch allowed the calculation of transport coefficients in the plasma phase, as electrical conductivity [17]. The table 1, next, gives the calculated values of electrical conductivity of a polyethylene plasma which allows in the range 5000 to 20 000 K and 0.1013 to 20.26 MPa. These tabulated values allow an estimation of the equilibrium temperature by interpolation with estimations or measurements of 1)electric current tube geometry, 2) electric resistance and 3) pressure.

Table 1 : Calculated values of electrical conductivity of a polyethylene plasma

P(MPa)\T(K)	5000	6000	7000	8000	9000	10000	15000	20000
0.1013	2.26994	40.0574	289.288	888.580	1814.070	2907.100	7962.670	11339.800
0.5065	1.24607	13.2157	134.884	511.010	1217.340	2230.570	8699.560	13805.700
1.013	1.36194	8.35777	90.6485	385.423	973.755	1883.130	8763.450	14892.700
2.026	0.248204	5.04281	58.0638	282.411	758.936	1540.290	8579.220	15857.800
3.039	0.147509	3.63636	43.9452	231.786	648.215	1351.160	8338.420	16287.200
4.052	0.110577	2.88121	35.885	199.938	576.511	1224.220	8112.540	16505.400
5.065	0.0913676	2.42003	30.621	177.456	524.749	1130.440	7904.360	16620.300
10.13	0.0573605	1.49303	18.7321	119.052	384.367	867.226	7101.190	16583.300
15.195	0.0463351	1.17217	14.1673	92.450	315.475	733.376	6548.650	16260.400
20.26	0.0404087	0.99932	11.6901	76.685	271.982	647.356	6133.750	15892.700

The energetic transfer in the interface (boundary limit, vapour layer, reaction zone) of the solid surfaces (liner of the torch, wall of the vessel or of the propellant grain) in contact with the gas phases (plasma, air/plasma mix or combustion products) may be estimated with the transport coefficients (thermal conductivity, viscosity, diffusion) in the gas phases. This model should be calibrated with experimental estimations of the energetic fluxes entering the surfaces. This coupling of theory with experiment may be tested, for instance, for gun propellant assuming an ablative model of combustion rate [$r_{ab}(\rho_m, \Phi_{th}, E_{ab})$], starting from a net energetic flux entering expression similar [$\Phi_{th} = A.P^n$] to the expression of the combustion rate [$r_{ab}=a.P^n$] itself, as mentioned in the literature. Then by successive iterations until satisfaction.

EXPERIMENTAL AND ANALYSIS

We present the results obtained on single base propellants, the estimation of their combustion rate and their analysis, a simple model of the energetic transfer to the wall to fit the experimental pressure curve.

The combustion experiments were performed in a 460 cm3 closed vessel, including a plasma torch 8 cm long and 1 cm in diameter, to generate plasma corresponding to an injected energy of 20, 30 or 40 kJ. The classical ignition is the same configuration as the above employing the hot wire method and a small amount of pyrotechnic igniting material. Taking into account the way to fill the vessel and the corresponding results mentioned in [18], we fill the propellant charge in the vertical vessel, which stands horizontally, unshaked.

Experimental combustion rates

For ETC ignition, classical STANAG 4115 method basic assumptions to determine the combustion rate are just modified with an initial pressure corresponding to the slope change in pressure, between the end of plasma injection without noticeable combustion of propellant (high temperature and low density gas phase) - equivalent to early stage of plasma-solid interaction and generation of decomposition products, proposed by [19] - and the beginning of the propellant combustion whose burning impose its pressure evolution (lower temperature and higher density of the gas phase).

The propelling charges tested at loading densities (LD) of 0.15, .225 and .3 (150, 225 and 300 kg/m3 in the volume of the vessel) were ignited all classically, .15 and .3 LD with two injected plasma energies of 20 kJ and 40 kJ, .225 LD with a 30 kJ plasma energy.

We draw the calculated value of combustion rate for a fraction of gun propellant burnt in the range 0 to 1 : the range 0 to 0.2 or 0.3 correspond to the ignition phase, the next range up to 0.7 or 0.8 correspond to the STANAG combustion rate which characterize the gun propellant, the last range up to 1 is after the web breakage with formation of slivers may indicate that some grain of propellant were modified by plasma. The black bold curves are for classic ignition. The grey (or red) bold curves are for 40 kJ ETC ignition and the thin grey (or purple) curves are for 20 or 30 kJ ETC ignition as presented below.

Large calibre 19 holes propellant grain

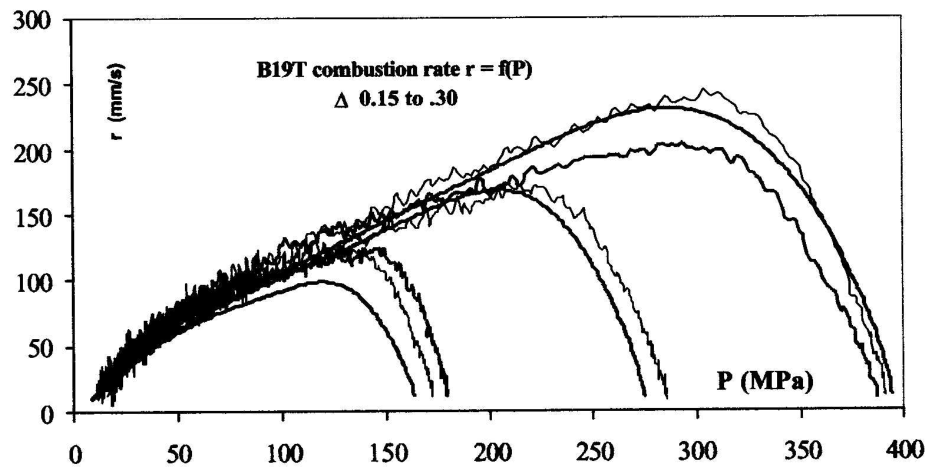

Figure 1 : STANAG type combustion rate of large calibre single base propellant.

Figure 1, shows the combustion rate of this single base propellant. For loading density of .15 combustion rates with ETC are higher than classic ignition. For loading density of .225 combustion rates with ETC or classic ignition are similar. For loading density of .3 combustion rates with 20 kJ ETC and classic ignition are similar ; with 40 kJ the combustion rate is lower than for classic ignition and may correspond to a modification of 12 % of the gun propellant grain during ETC ignition.

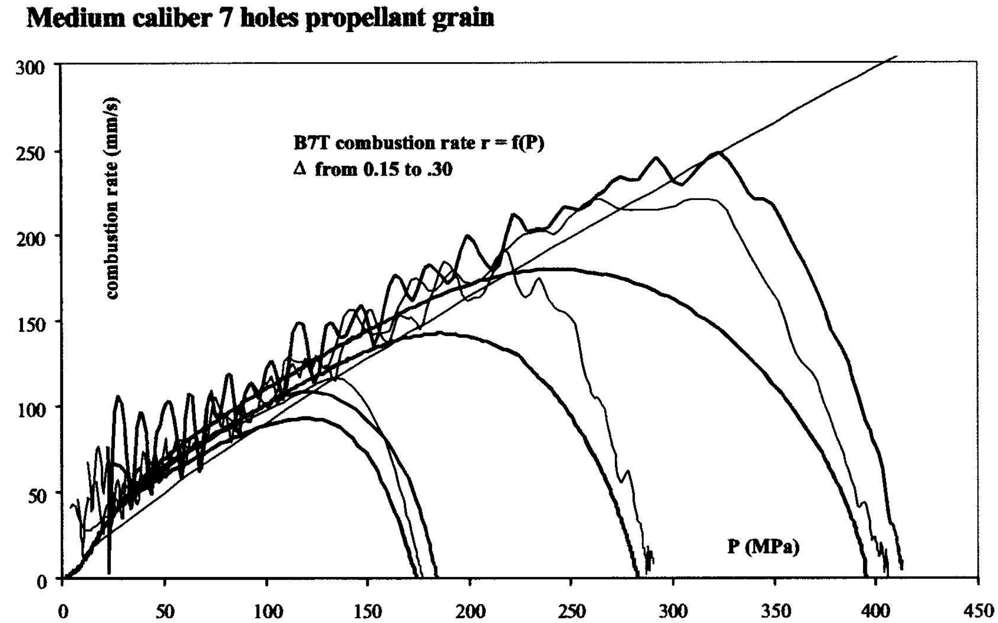

Figure 2 : STANAG type combustion rate of medium calibre single base propellant.

Figure 2, shows the combustion rate of this smaller size single base propellant. For all loading density the combustion rates with ETC are higher than for classic ignition. There is no apparent modification of the gun propellant grain during ETC ignition.

Numerical simulation of energy transfer

To estimate combustion rate with STANAG 4115 method, we start from experimental pressure, knowing the form function of the propellant grain, estimating the heat losses proportional to the mass of the propellant burnt.

We achieve a simple numerical simulation which uses the experimental pressure data to calculate the reaction rate of the propellant from its STANAG combustion rate r_s, then the matter and energy release, the energetic transfers to and inside the wall and in the gas phase to have an estimation of the pressure and the temperature of the gas phase. The expression for energetic flux Φ_{th} to the wall, depends on pressure P_g and temperatures of the gas phase T_g and the wall T_w : $\Phi_{th} = Kphi. P_g.(T_g - T_w)$, with Kphi constant.

The thin black experimental pressure curve in the Figure 3, presents a little pressure accident at maximum pressure, maybe due to fluid dynamics. The bold simulated curve with STANAG combustion rate is a higher limit of the experimental curve as it is higher than the experimental curve up to more than 100 MPa, and then joins it.

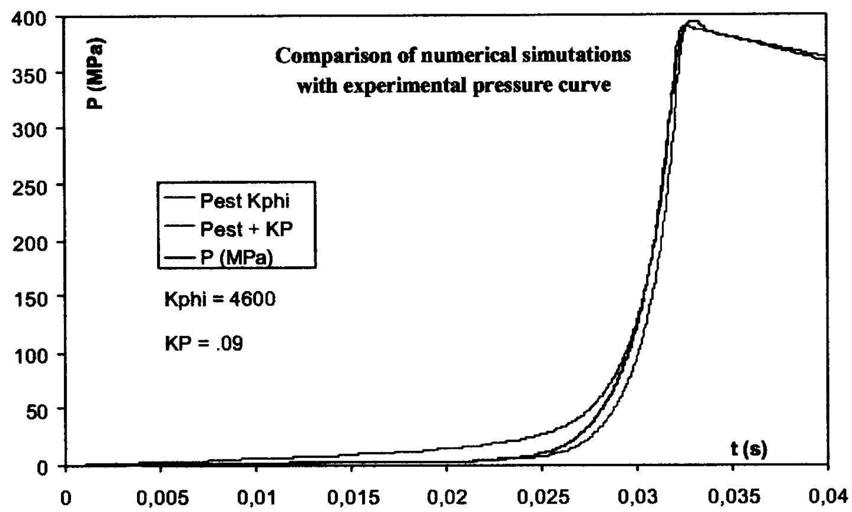

Figure 3 : Comparison of numerical simulations and experimental pressure curve.

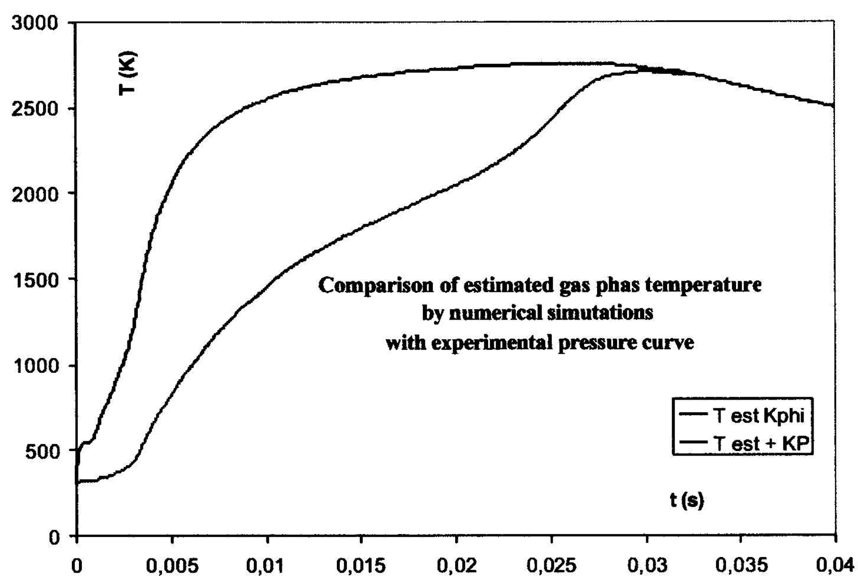

Figure 4 : Comparison of temperature estimation of the numerical simulations

As shown by the upper experimental results, for classical ignition, the combustion rate at low pressure is always below the STANAG combustion rate. An explanation, analogous to upper for reaction zone, is that at low pressure the energetic feedback is lower than STANAG and comes only from a fraction of the reaction zone length. The corrected combustion rate r_{cor} may be expressed with STANAG combustion rate $\mathbf{r_s}$ multiplied by a corrective factor as $(1-e^{-KP.Pg})$, KP being a constant. The corresponding bold simulated curve with such STANAG corrected combustion rate is a lower limit of the experimental curve as it is joined with the experimental curve or lower from 0.025 s until maximum pressure.

In Figure 4 are represented the estimated temperatures of these two simulations versus time. They join after maximum pressure (due to the good fitting of the energetic flux once all the propellant is burnt). The STANAG one is higher than STANAG corrected one, it is obvious as the release of matter and energy to the gas phase is higher. The STANAG corrected temperature fits well the experimental pressure curve until 0.025 s and may be a realistic estimation in this range. The following simulations curves should keep the fitting obtained with the experimental curve and fit it better between 0.025 s and maximum pressure or, more simply, border (by a upper and a lower limit curves) more closely the experimental curve.

DISCUSSION - CONCLUSION

The experimental results obtained with a manometric closed vessel coupled with physics allows :

- to estimate combustion rate of gun propellant,
- to evaluate the physical models used for combustion rate modelling,
- to estimate energetic fluxes involved in combustion rate and energetic losses to the wall.

It shows that the closed vessel is still an essential experimental device for interior ballistics, as presented [20] at EFBP in 2000. It is also valuable for modelling purposes of the ignition phase itself (classical, plasma ignition - configuration of the plasma impingement on the propelling charge [18] or plasma injection after ignition [19] or after completion of burning of the propelling charge) and the combustion phase.
The evolution of CFD modelling and computing science allows now the possibility of 3-D modelling for IB. Nusca and al. [21] presented the beginning of this work at 19 th ISB.

Nowadays, the numerous international publications on ETC ballistics and plasma/ propellant interactions show that physical models explaining experimental results are still researched. And peculiar experimental results are still necessary to evaluate, calibrate and validate these models.

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