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SINGULARITIES OF BURNING RATE DETERMINATION OF FINE-GRAINED PROPELLANTS

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Internal ballistic analysis usually assumes that propellant grains are all of the same size and configuration, and they are ignited uniformly with all surface areas of the grains exposed. According to these assumptions the burning rate of propellant is determined from closed vessel tests. The burning rate law coefficients may be calculated from differentiation or integration of experimental pressure-time curve obtained from closed vessel testing. Different fine-grained propellants were fired in closed vessel tests to determine their burning rate behaviour. In order to determine burning rate law coefficients the variations in mass of igniter material (black powder) and variations in initial temperature of propellant at the same value of loading density were used. The rate of pressure change and dynamic vivacity calculations obtained from closed vessel experiments let us understand the physics of the interaction of involved energy from igniter material with gun propellant and report the influence of the phenomena on values of burning rate coefficients.

INTRODUCTION

It is a commonly known fact that interior ballistic trajectory simulation of projectiles and engineering design process of a barrel are realised on the basis of input data partly provided by mathematical solution of the thermodynamic interior ballistic model with global parameters [1]. In the case of geometric, regular shape of propellant grains with smooth unburned surface S_1 and unburned volume V_1, the mass fraction burning rate (one of the interior ballistics governing equations) may be expressed as

$$\frac{dz}{dt} = \frac{S_1}{V_1} \cdot \Phi(z) \cdot r(p) \qquad (1)$$

Accurate knowledge on the form of propellant burn law *r(p)* and values of its coefficients (and also form function *Φ(z),* specific energy and covolume) plays a fundamental role in understanding of internal ballistics calculations. The burning rate of a propellant (the rate of reduction in size of the propellant with time) varies with pressure *p*, and this variation is usually approximated by:

- the linear burning rate law [2] very popular in East European ballistics laboratories

$$r = r_1 \cdot p \tag{2}$$

- or the burning rate law [3]

$$r = \beta \cdot p^{\alpha} \tag{3}$$

The major assumptions [2,4] used in internal ballistic (burning rate) analysis are:

1. The propellant gas mixture is described by the Noble-Abel equation of state;
2. Propellant grains are all of the same size and configuration;
3. All propellant grains are ignited uniformly, with all exposed surface areas of the grains having recessed by a small distance;
4. All exposed burning surfaces recede at a uniform rate, implying that all grains shrink symmetrically;
5. Decomposition of a unit mass of propellant always liberates the same amount of energy, which heats product gases to the same temperatures.

In the case of geometric, regular shape of propellant grains with smooth surface, the burning rate coefficients r_1, β and α (eq. 2 and 3) of propellant may be calculated from the experimental pressure-time curve *p(t)* of the closed chamber firings, average properties (e.g. length, radius, etc.) of grains and the following equations

- using integrated pressure-time curve - according to [2]

$$r_1 = \frac{e}{I} = \frac{e}{\int_{t_a}^{t_b} p\,dt} \tag{4}$$

where: e– total (e_1) or limited layer of burnt propellant (regression distance e_{a-b} of propellant granule);

I – total I_1 (for total layer e_1) or limited I_{a-b} (for limited layer of burnt propellant e_{a-b} and limited fraction of mass burned z_{a-b}) impulse of pressure of propellant gases; for total impulse calculated from the start to the end of propellant combustion (process of gas creation);

- and, according to [3], with the differentiated pressure-time curve

$$r = \frac{de}{dt} = \frac{de}{dz} \cdot \frac{dz}{dp} \cdot \frac{dp}{dt} \tag{5}$$

where:- the change in regression distance with fraction burnt (*de/dz)* is calculated from a form function;
- burnt mass change with pressure (*dz/dp*) is calculated from the Noble-Abel equation of state;
- the rate of change of pressure (*dp/dt*) is obtained from a closed vessel experiment.

The aim of this work is to investigate closed vessel tests, which permit to see the differences in progress of propellant ignition period. For this purpose different ignition systems were used.

GRAIN GEOMETRY

This paper uses some conventional fine-grained propellants (Table 1) to demonstrate any peculiarities of burning rate determination.

Table 1. Average dimensions (in mm) of investigated propellant grains

Average dimensions of grain (producer's declaration)	Single-base propellant (tube)			Double-base propellant D (square plate)
	A	B	C	
Total layer (1/2 of web size)	0,1625	0,185	0,76	0,08
Inside diameter	0,15	0,25	1,91	-
Length	1,9	6,2	75	1,2

Producer's declaration on average properties of very small, tube grains does not correspond with the facts. Tolerances in propellant manufacture can result in variation of dimension and shape of propellant grains throughout a charge. First of all it is shown for propellant A. Some possible imperfections (Figure 1) that may occur are as follows: visible lack of the entrance of the inside hole (on the left), partially blocked entrance (on the right) or displacement of the inside hole towards the outside surface of grain (in the middle). This situation may be the reason of inaccuracy in burning rate calculations. The other grains (propellants B, C and D) are more regular geometrically. The results of the comparison between experimental investigations of propellants (A, B, C and D) using different ignition methods are presented in this paper.

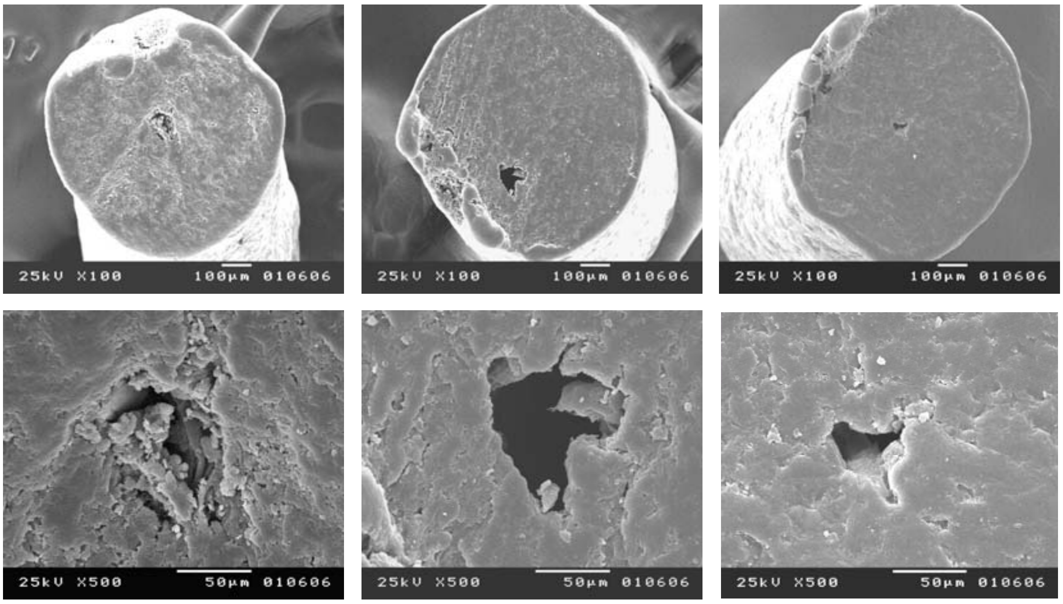

Figure.1 Examples of real shapes of analysed fine-grained, tube propellant A.
Front surface of grain (top) and the entrance of the inside hole (bottom).

CLOSED VESSEL TESTS

Closed vessel tests are a good method of obtaining burning rate information for propellants. These experiments measure gas generation rates and therefore the burning rate information can only be accurately deduced if conditions of tests precisely meet the major assumptions of internal ballistic analysis. Experimental pirostatic investigations were carried out in a vessel of 200 cm^3 for only one loading density (100 kg/m^3). Technical parameters of the used closed vessel, a pressure measurement system consisting of a piezo-electric transducer (HPI 5QP 6000M), a data acquisition chain (amplifier, A/D converter, computer), and also the methodology of investigation were the same as described in [3]. An ignition system consisted of a power source and an ignition material. Black powder was the ignition material. Adequate formal standards and regulations [2, 3, and 5] recommend different conditions of ignition. Cotton bag containing 0,5÷2 g of black powder (the mass depends on loading density) is a rule but the general conclusion given in [2] is that *"...all propellant grains are ignited uniformly, with all exposed surface areas only at ignition pressure 12-15 MPa."* (it means 8÷10 g of black powder). Therefore it was decided to carry out closed vessel tests in which the ignition systems with various masses of black powder (only electric match without black powder or electric match and 2g, 4g, 6g or 8g mass of black powder) were used.

CALCULATIONS

Experimental vivacity

The pressure-time data from the closed vessel firing were used to calculate the experimental vivacity and burning rate behaviour of the propellants. The results of experimental vivacity L_{exp} calculations (for propellants A, B and C with initial temperature 293 K), obtained by using the following equation

$$L_{\exp} = \frac{1}{p_z} \cdot \frac{dz}{dp} \cdot \frac{dp}{dt} = \frac{1}{p_z} \cdot \frac{dz}{dt} \qquad (6)$$

are shown in Figure 2. The shape of the experimental vivacity curves shows a level profile only for propellant C, indicating that the propellant surface area was constant during most of the burning process.

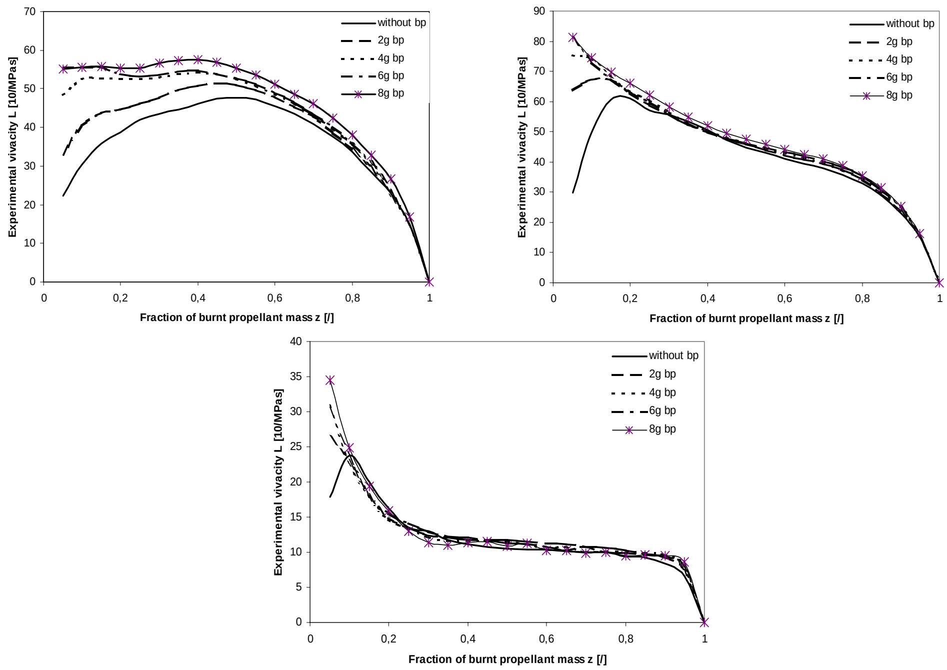

Figure 2. Experimental vivacity behaviour for propellant A (top-left), B (top-right) and C (bottom)

In this case the larger tube grains of propellant C are more regular geometrically, without the imperfections typical of fine-grained tube propellants and ignition gases have easier access to the surface of these grains. Real ignition process of propellant

A (in the case of small mass of black powder) does not meet theoretical assumptions but significant increase of black powder mass during closed vessel firings creates better and better conditions of ignition process becoming close to the theoretical model of propellant burning. This is the reason for changes in the nature of burning process, particularly in a period of propellant ignition, and finally it may be the reason of changes in burning rate determination. It seems probably that the assumption that all propellant grains are ignited uniformly, with all exposed surface areas of the grains may be performed by a gaseous ignition system [6]. The ignition mixture (for example CH_4-0_2) permits to treat ignition process of propellant according to presented above assumption and additionally permits to discriminate the combustion properties of two parts of the particles (in deterred propellants).

Burning rate laws (eq.2 and eq.3)

Comparison of values of linear burning rate law coefficient r_1 for different masses of black powder and for two calculating methods (from total or limited impulse of pressure – eq.4) is shown in Table 2.

Table 2. Values of r_1 coefficient (for linear burning rate law)

Propellant		r_1 x10^{-9} [m/(sPa)]				
		0g	2g	4g	6g	8g
A	Total impulse	0,45	0,53	0,56	0,60	0,68
	Limited impulse	0,70	0,78	0,88	0,94	1,01
B	Total impulse	0,52	0,61	0,65	0,69	0,74
	Limited impulse	0,82	0,90	0,95	1,04	1,07
C	Total impulse	0,67	0,86	0,95	1,02	1,06
	Limited impulse	0,84	0,92	0,97	1,06	1,05

The graphs in Figure 2 may constitute the basis for determination of integration borders of limited impulse for coefficient r_1 calculation (eq.4). In the investigated case the value of the right border (z_b=0,8) corresponds to the maximum value of *dp/dt* on experimental pressure-time curve and the value of the left one (z_a=0,2) corresponds to the beginning of fully developed process of propellant burning. So far coefficient r_1 of linear burning rate law (for a given propellant) has been treated in East European ballistics laboratories as constant during for whole process of propellant combustion and this form has been used in interior ballistics governing equations.

Coefficient r_1 behaviour throughout the process of burning propellant ($0 \le z \le 1$) may be obtained using transformed mass fraction burning rate equation (7)

$$r_1 = \frac{dz}{dt} \cdot \frac{V_1}{S_1} \cdot \frac{1}{\Phi(z) \cdot p_z} \tag{7}$$

Performed calculations show similar coefficient r_1 behaviour to the experimental vivacity behaviour (Fig.2) also for other initial temperatures of propellant. It means that coefficient r_1 can not be treated as constant during internal ballistic simulations.

Examples of the burning rate behaviour (calculated on the basis of eq.5) for all propellants (A, B, C and D) are shown in Figure 3.

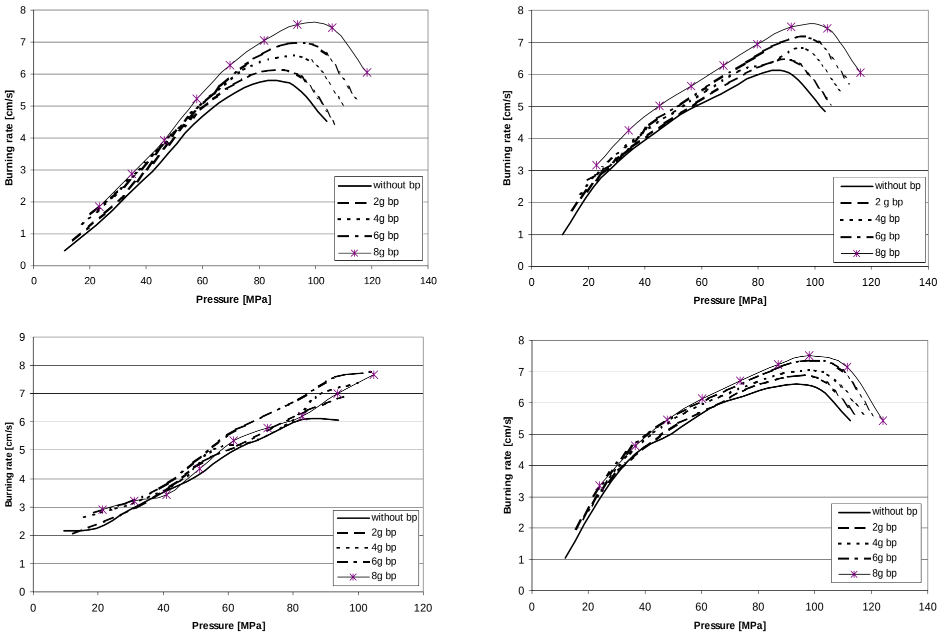

Figure 3. Burning rate behaviour for propellant A (top-left), B (top-right), C (bottom-left) and D (bottom-right)

Figure 3 shows the differences between the determined burning rate curves for each investigated propellant especially in fully developed combustion process but aforementioned differences decrease when more regular shape of propellant grains are combusted. Large tube grains (propellant C) and square plate grains (propellant D) are more regular geometrically, without the imperfections typical of fine-grained tube propellant (A) and ignition gases have easier (in contrast to propellant A) access to all surface of grain. On the other hand larger mass of black powder also means larger dose of energy transported to propellant surface in the first period of propellant combustion. It is a commonly known fact that ignition pressures in cartridges are larger than the closed vessel tests. It means that coefficients α and β may have different values if closed vessel tests are performed with using of different ignition systems and propellant may be burnt with another rate.

CONCLUSION

The results of experimental tests and calculations presented in this paper show significant influence of the used type of ignition system (mass of black powder) on burning rate of propellant (especially fine-grained propellant). Differences in burning rate calculations may be the reason of considerable errors in theoretical calculations of pressure-travel and velocity-travel curves during internal ballistic computer simulations of a gun system. They might also mean errors in muzzle velocity calculations, and finally changes in projectile range. It is interesting that the used various types of ignition system do not influence the temperature factor determination [7].

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