Influence of ignition method and loading conditions in closed vessel tests on the burning rate of a propelling charge

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Abstract. *Ignition process of granular propellant charge in gun propellant system is the essential step in the whole interior ballistic cycle and igniter is the very important element of ignition system. The task of igniter is to give propellant charge essential energetic impulse in time and space, which should provide uniform ignition of all propellant grains. Realisation of this task depends on many factors: mass and type of ignition material in igniter, igniter locations and dimensions, number and diameter of side holes of propellant grains etc.*

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 the possible influence of the ignition system and loading density on the combustion rate was investigated. Different ignition systems have been used for the characterization of ignition phase in closed vessel tests. Basic closed vessel experiments were carried out in a conventional closed vessel (CCV) of 200 cm^3. Ignition systems with various mass of black powder were used. Comparable experiments were carried out in a micro-closed vessel (MCV) of 1,786 cm^3 and vented closed vessel (VCV) of 200 cm^3.

1. Introduction

The characteristic pressure-travel and pressure-time curves of a gun propellant system (description of interior ballistic trajectory of projectile inside the barrel) are dependent upon many factors: variation in chemical composition of a propellant, ignition characteristics, propellant grain characteristics, loading conditions (charge weight variations), and variations in burning rate of a propellant etc [1].

In the case of geometric, regular shape of propellant grains with initial volume V_{g1} and surface S_{g1}, to obtain a complete picture of the internal ballistic cycle, a form of the burning rate law r is needed to calculate (for form function $\Phi(z)$ defined as the ratio of the current burning surface area S_{gz} to the initial surface area S_{g1}) the mass fraction burning rate of propellant, which may be expressed as

$$\frac{dz}{dt} = \frac{S_{g1}}{V_{g1}} \cdot \Phi(z) \cdot r(p)\,, \tag{1}$$

The burning time of a propellant grain can be controlled by several means: the size and shape of the propellant grain, the number of perforations in each grain, the web thickness and the rate of burning, which is dependent on pressure gases surrounding the propellant grain. Accurate knowledge of burning rate r of propellants plays a fundamental role in simulation and understanding of internal ballistics phenomena.

The burning rate (the rate of reduction in size of the propellant with time) increases as the pressure increases. The linear burning rate vs. pressure behaviour of a gun propellant (known as burning rate law) is a characteristic of the propellant composition. It is know that various forms of a burning rate law have been proposed in fundamental books and technical documents relating to internal ballistic trajectory simulation of projectile and examination of propellant. Experimental and theoretical study of propellant burning rate indicates that there are limitations to the validity of the linear approach of burning rate law [2,3]. Therefore the most widely is the burning law expressed as exponential dependence on pressure [4,5]

$$r = \beta \cdot p^{\eta} \tag{2}$$

where η is the pressure index and β is the burning rate constant of the propellant composition.

2. The content and method of the experiment

The burning characteristics of propellants need to be definitively determined for assessment of gun performance. Closed vessel tests are 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 thermodynamic and geometrical assumptions (equation of state, geometrical model of combustion, average properties of propellant grains) of internal ballistic analysis [4,6]. In the case of geometric, regular shape of propellant grains with smooth surface, the burning rate coefficients β and η of propellant may be calculated [7] on the basis of the differentiated smoothed, experimental pressure-time curve $p(t)$ of the closed chamber firings and the equation:

$$r = \frac{de}{dt} = \frac{de}{dz} \cdot \frac{dz}{dp} \cdot \frac{dp}{dt}, \tag{3}$$

where: - the change in regression distance with fraction burnt (*de/dz*) calculated from a form function $\Phi(z)$ as

$$\frac{de}{dz} = \frac{V_0}{S_0} \cdot \frac{1}{\Phi(z)}, \tag{4}$$

- the change of mass burnt with pressure (*dz/dp*) calculated from the Noble-Abel's equation;

$$\frac{dz}{dp} = \frac{1}{p_{\max}} \cdot \frac{1 + \left(\alpha - \frac{1}{\rho}\right) \cdot \frac{p_{\max}}{f}}{\left[1 + \left(\alpha - \frac{1}{\rho}\right) \frac{p}{f}\right]^2}, \tag{5}$$

where α, f, ρ, p_{max}, are the covolume, the force (both parameters of Noble-Able's equation of state), the propellant density and the maximum experimental pressure respectively.

The rate of change of pressure (*dp/dt*) is obtained from a closed vessel tests. Equation (3) can be curve-fitted to this date and coefficients β and η determined: if the values of log(r) are plotted against log(p), the gradient of the best-fit straight line will give η and antilog(β) will be the intercept point. Up to now, the closed vessel procedure for determination of propellant burning properties for use in interior ballistic calculations (absolute measurements) and for comparative purposes (relative measurements) is based [7,8] on experimental pirostatic firings, which are done for limited range of loading densities (usually Δ = 100 and/or 200 kg/m^3), or on basis of three loading densities, each separated by 30 kg/m^3 (the central value of the loading density should be commensurate with the weapon system pressure).

The ignition system shall consist of a power source and the igniter material. Black powder is the ignition material usually. Adequate formal standards and regulations [7,8] recommend different conditions of ignition but cotton bag containing (0,5 ÷ 2) g of black powder (the mass depends on loading density) is the rule.

Closed vessel tests at about loading densities of (100 or 200) kg/m^3 are often conducted under conditions that are far different from assumptions of internal ballistic analysis and are far different from those encountered in a gun system:

- producer's declaration on average properties of very small grains (fine-grained propellants) does not correspond with the facts. Tolerances in propellant manufacture can result in variation of dimension and shape of propellant grains throughout a charge [9];
- real ignition process of propellant realised during closed vessel tests does not meet theoretical assumptions of propellant burning model;
- in reality the loading density for gun propellant systems is significantly higher.

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.

Closed vessel investigations were carried out in three different vessels:

- classical closed vessel (CCV) of 200 cm^3;

- micro-closed vessel (MCV) of 1,786 cm^3, constructed on the basis of 7,62-mm machine gun barrel that was cut down to reduce the internal volume. In this case standard primer ignited the propellant;
- vented closed vessel (VCV) of 200 cm^3. It can routinely be used at pressure of 400 MPa and is equipped in a blow-off valve. If the maximum pressure is reached, the blow-out disk of the valve opens automatically and rapidly releases nearly all the energy.

Technical parameters of the used pressure measurement system, consisting of a piezo-electric transducer (HPI 5QP 6000M) and data acquisition chain (amplifier, A/D converter, computer), were the same as described in [7]. An ignition system in CCV and VCV vessels consisted of a power source and an ignition material.

3. Discussion of results

3.1. CCV and MCV test results

Experimental investigations of the fine-grained, single-base propellant A (Table 1) were carried out in CCV and MCV vessels at different ignition methods (Table 2) for one loading density (100 kg/m^3).

Table 1. Chemical composition of analysed single-base propellant A

Ingredient	[%]
Nitrocellulose N = (13,17 ÷ 13,21) %	93
Volatile substances	max 3,3
Diphenylamine	1,0 ÷ 2,0
Camphor	max 1,8
Graphite	max 0,28

Table 2. Used ignition system in CCV and MCV tests

Closed vessel	CCV			MCV
Type and description of ignition system	A	B	C	D
	only electric match (without black powder)	plastic bag containing 2g of black powder	plastic bag containing 2g of black powder	standard primer
Propellant position inside of CV	loaded loose	loaded loose	bagged in company with black powder	loaded loose

The results of measured pressure $p(t)$ are shown in Figures 1. In this case, pressures p_{max} take into account the pressure coming from ignition system (p_{ign}). The pressure-time data from the CCV and MCV vessels were used to calculate the dynamic vivacity and burning rate behaviour of the propellants. Vivacity curve encompasses both geometry variation and burn rate variation with regression distance. The shape of the curve indicates whether the propellant is progressive (increasing gas generation rate through the firing), degressive (reducing gas generation rate) or neutral.

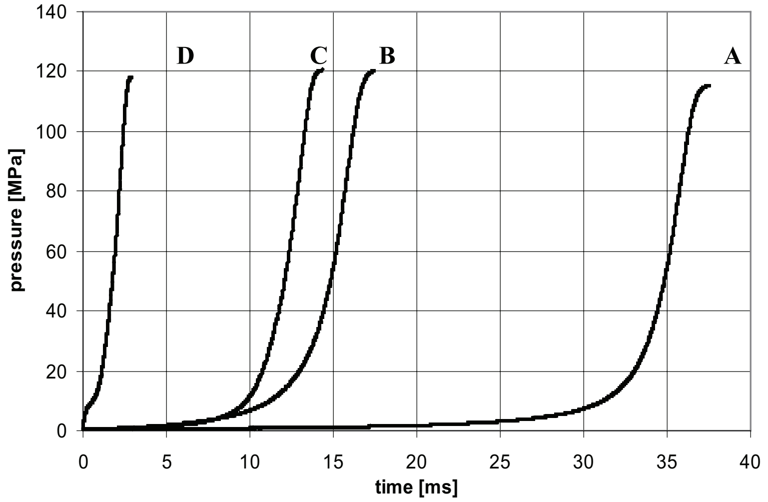

Fig. 1. Pressure vs. time curves from closed vessel tests for different (A, B, C and D) systems of ignition

Results of dynamic vivacity L calculated from below equation [6,7]

$$L = \frac{1}{p_z} \cdot \frac{dz}{dt} = \frac{1}{p_z} \cdot \frac{dz}{dp} \cdot \frac{dp}{dt}, \quad (6)$$

are shown in Figure 2 and results of burning rate *r(p)* calculated from equation (3) are shown in Figure 3.

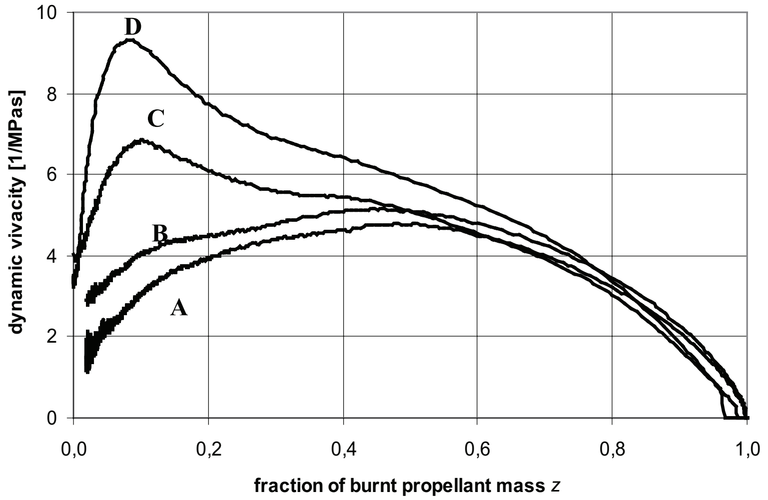

Fig. 2. Dynamic vivacity *L(z)* curves for different (A, B, C and D) systems of ignition

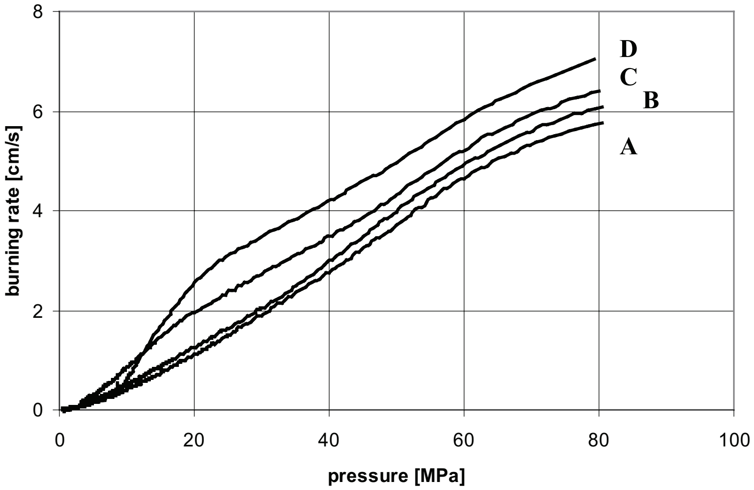

Fig. 3. Burning rate u(p) curves for different (A, B, C and D) systems of ignition

The ignition systems with various mass of black powder (only electric match without black powder or electric match and (2, 4, 6 or 8) g of black powder – Table 3) were used in the next experimental work.

Table 3. Used ignition system in CCV tests

Closed vessel	CCV				
Type and description of ignition system	A	B1	B2	B3	B4
	only electric match (without black powder)	plastic bag containing black powder			
		2 g	4 g	6 g	8 g
Propellant position inside of CV	loaded loose	loaded loose			

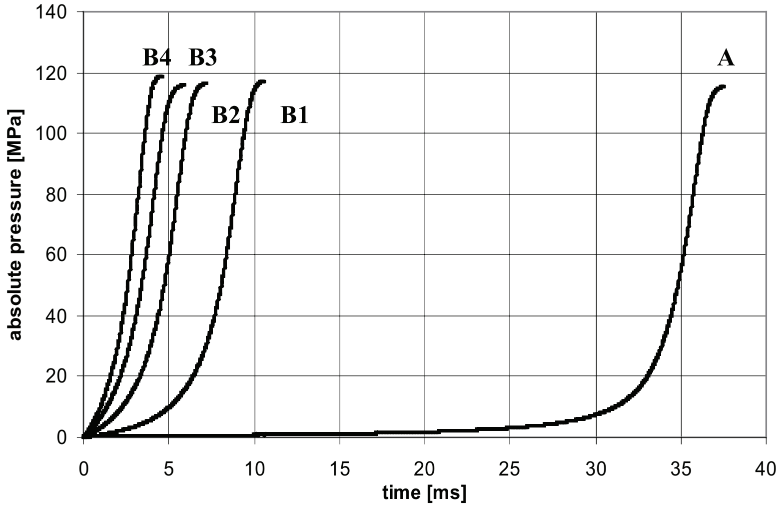

Fig. 4. Pressure vs. time curves from closed vessel tests for different (A, B1-B4) systems of ignition

The results of absolute pressure $[p\text{-}p_{ign}](t)$, dynamic vivacity $L(z)$ and burning rate $r(p)$ of investigated, single-base propellant (Table 1) at different ignition methods (Table 3) are presented on Figures 4-6.

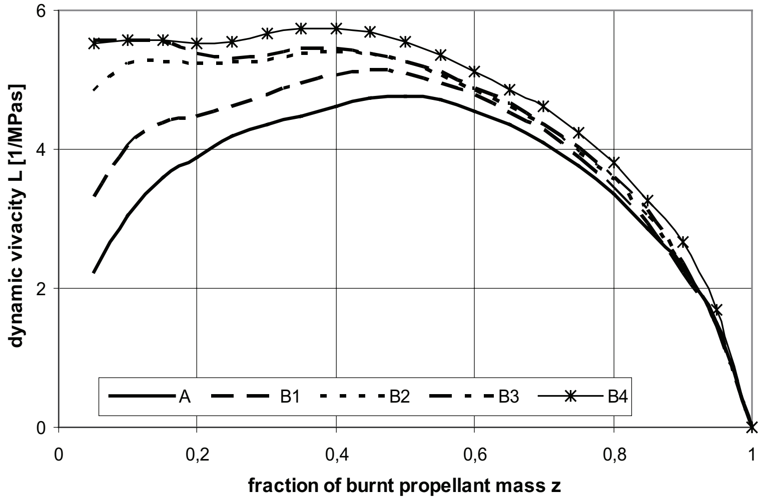

Fig. 5. Dynamic vivacity *L(z)* curves for different mass of black powder

The pressure-time data from the closed vessel were used to calculate the dynamic vivacity and burning rate behaviour of investigated propellant. Dynamic vivacity *L* was calculated from equation (6) and is shown on Fig. 5.

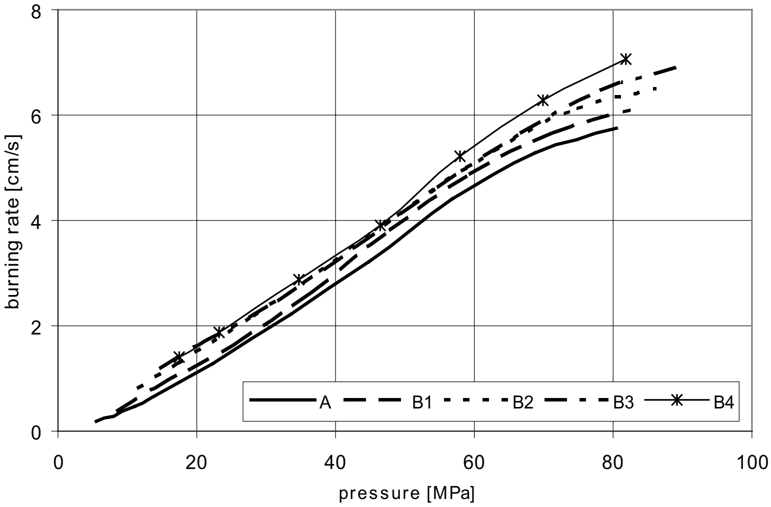

Fig. 6. Burning rate r(p) curves for different (A, B1-B4) systems of ignition

In the case of conventional closed vessel tests, ignition process of propellant A - for electric match as igniter only - does not meet theoretical assumptions. Significant increase of black powder mass - range of (2 ÷ 8) g - during closed vessel firings creates better and better conditions of the ignition process becoming close to the theoretical model of propellant burning. Larger mass of black powder at the same loading density (the same total surface of propellant grains) in conventional closed vessel tests means larger dose of energy transported to propellant surface in the first period of propellant combustion, but these ignition systems (description of graph: *B1-B4*) and loading conditions are not comparable to the ones used in the actual combustion chamber of guns unfortunately.

In the case of MCV tests (description of graph: *D* – Figures 1-3), the standard primer ignites the propellant. The largest dynamic vivacity and combustion rate are observed when using standard primer of machine gun cartridge. It is a commonly known fact that ignition pressures in cartridges are larger than the closed vessel tests and propellant may be burnt with another rate.
It means that coefficients η and β may have different values if closed vessel tests are performed with using of different ignition systems.

3.2. CCV and VCV test results

Experimental investigations of the seven-tubed, single-base propellant B (Table 4) were carried out in CCV and VCV vessels at the same ignition method (Table 5) for different loading densities. The results of pressure *p(t)* and burning rate *r(p)* are presented below.

Table 4. Chemical composition of analysed single-base propellant B

Ingredient	%
Nitrocellulose N = (13,08÷13,15) %	94,7
Volatile substances	max 3,3
Diphenylamine	1,0÷2,0

Table 5. Used ignition system in CCV and VCV tests

Closed vessel	CCV		VCV	
Loading density Δ [kg/m^3]	75	225	300	700
Type and description of ignition system	plastic bag containing 2g of black powder			
Propellant position inside of CV	loaded loose			

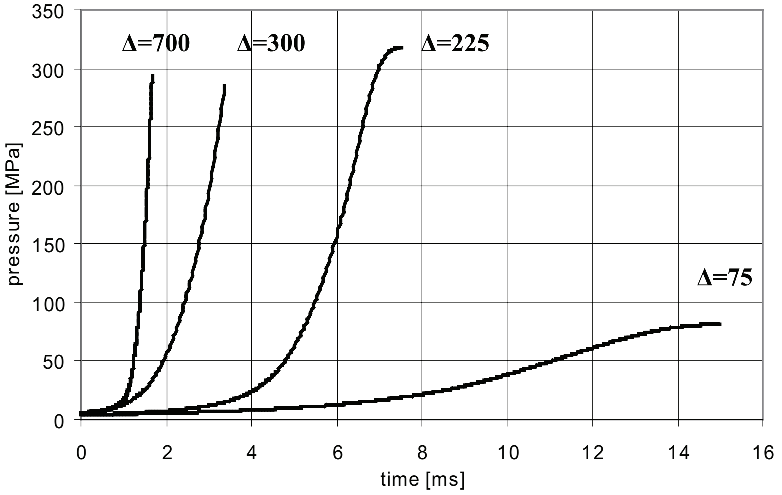

Fig. 7. Pressure vs. time curves from CCV and VCV vessel tests for different loading densities

Figure 8 shows the differences between the determined burning rate curves for propellant B combusted at different loading densities (75 and 700 kg/m^3) but ignited the same mass of black powder. The graphs show burning rate curves for initial process of propellant burning, directly after ignition. It is observed that larger combustion rate is characteristic of smaller loading density.

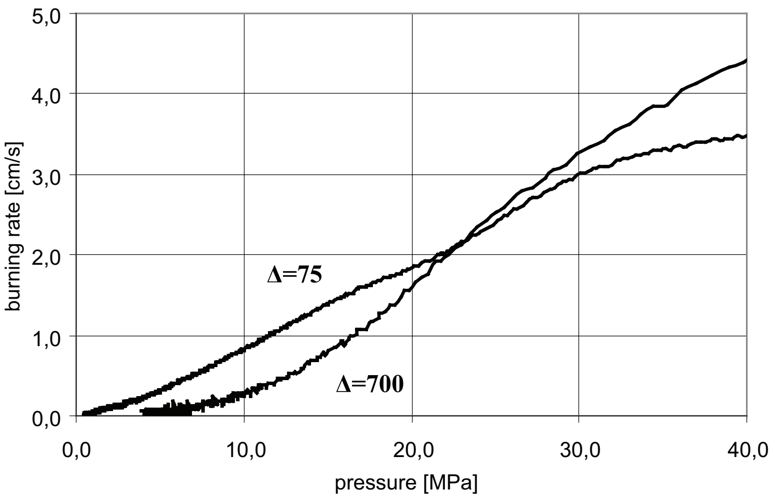

Fig. 8. Pressure vs. time curves from CCV and VCV vessel tests for extreme loading densities

For the same mass of igniter material (black powder) but for different loading densities, the initial surface of all grains of propellant for loading density 75 kg/m^3 is some times smaller then initial surface of all grains for loading density 700 kg/m^3.

When ignition gases (*ign*) surround the propellant (*prop*), the net radiation between gases and propellant may be written as

$$\frac{dq_r}{dt} = c \cdot E \cdot S \left[\left(\frac{T_{ign}}{100} \right)^4 - \left(\frac{T_{prop}}{100} \right)^4 \right], \tag{7}$$

which implies that the needed rate of radiate heat flow varies with the area S, as well as the fourth power of the temperature of the radiating body. It means that:

- for smaller loading density and for the same mass of igniter charge, and
- for the same loading density and for growing mass of igniter charge,

are created better conditions of heat transfer between hot ignition gases and propellant surface and in consequence better conditions to meet theoretical assumptions used in burning rate analysis.

4. Conclusion

4.1. Observed differences in burning rate calculations may be a reason of significant errors in theoretical calculations of pressure-travel curve. Closed vessel data is typically obtained at lower loading densities so at lower pressures than obtained in gun system. Therefore extrapolation of formulated burning rate laws to a gun system usually yields poor results unless some adjustments are made.

4.2. Internal ballistic modelling requires good characterisation of the burning behaviour of gun propellants. Ideally one would like to ignite all propellant grains at the same time. Closed vessel tests with limited mass of black powder as igniter are rather conducted under conditions that are far different from those encountered in a gun system.

4.3. It seems that both:

a) the MCV solution (conventional or vented) equipped with selected primer as ignition system;
b) the VCV solution equipped with selected igniter for investigation in wide range of initial loading densities;

may be good instruments to describe the real burning rate in different periods of propellant combustion. It is very probably that all propellant grains could be ignited uniformly then, with all exposed surface areas of the grains.

Acknowledgement

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