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ODDITIES IN DETERMINING BURNING RATE ON BASIS OF CLOSED VESSEL TESTS OF SINGLE BASE PROPELLANT

Zbigniew K. Leciejewski
Military University of Technology, Faculty of Mechatronics and Aerospace, Warsaw, Poland
e-mail: zbigniew.leciejewski@wat.edu.pl

The proper determination of parameter values defining the dependence of the burning rate r of smokeless propellant on gas pressures p surrounding the burning grains constitutes one of the goals of experimental pyrostatic (closed vessel) testing. The aim of the hereby paper is the analysis of results of experimental closed vessel tests realized in the context of isolating possible oddities in determining the relation $r(p)$. During the experimental tests, a single base propellant with grains of different or similar combustible layer thickness e_1 was burned while implementing identical or various loading conditions. Identical ignition systems were used in both instances. The results of experimental tests and theoretical analysis performed permit a more complete verification of the assumptions with regard to proper realization of pyrostatic comparative tests and prove additionally that closed vessel tests should be focused in the direction of "dedicated" tests.

Keywords: internal ballistics, closed vessel test, smokeless propellant, burning rate law

1. Introduction

The burning rate of the smokeless propellant within high-pressure environments (magnitude of tens or hundreds of MPa) within the barrel during firing is one of the significant ballistic characteristics permitting proper theoretical analysis of barrel propellant systems.

The mathematical model widely used for purposes of this analysis, within the thermodynamic aspects established by Serebryakov (1949) and Corner (1950), clarified by Baer (1979), Tuomainen (1996) and Military Agency for Standardization in STANAG 4367 (2000), does not provide direct correlations between properties of the igniting material and the ignition mechanism of propellant grains and the intensity of the formation of propellant gasses released from the propellant being subjected to combustion.

In this model, assuming the simultaneous and instantaneous ignition of all grains of the propellant charge, the rate of propellant burning r is (for its standard initial temperature) only a function (linear or exponential) of the gas pressure p surrounding the burning propellant grains.

To obtain a complete picture of the internal ballistic cycle, the burning rate law r to calculate the mass fraction burning rate of the propellant is needed. 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

$$\frac{dz}{dt} = \frac{S_1}{V_1}\Phi(z)r(p) \tag{1.1}$$

Accurate knowledge on the form of the propellant burning law $r(p)$ and values of its coefficients (and also form function $\Phi(z)$, specific energy and covolume) plays the fundamental role in the determination of the burning rate of propellants and simulation of internal ballistics. The proper determination of the parameter values describing the function $r(p)$, by combustion of a specific propellant mass in adiabatic and isochoric conditions, constitutes one of the main goals of experimental pyrostatic (closed vessel) testing. The conditions of realization of such tests do however differ with regard to the process of firing from a real barrel propellant system. The following constitute significant differences:

a) combustion of a propellant in pyrostatic testing takes place in closed volume conditions, while during firing within a barrel propellant system – within the variable volume resultant from the motion of the projectile, with the propellant gasses performing the work associated with propelling the projectile within the barrel;

b) the initial loading density within the propellant system ($\Delta \approx 1000\,\mathrm{kg/m^3}$), meaning the ratio of the propellant mass to the initial volume of the cartridge chamber is much greater than during the standard pyrostatic testing ($\Delta = 100$-$200\,\mathrm{kg/m^3}$);

c) the propellant ignition system used during pyrostatic testing is not adequate (in terms of, among others, the mass and type of the igniting material) to the ignition system used in real ammunition.

The above represents that the values of the $r(p)$ function parameters, obtained by way of the standard pyrostatic testing, must be – within the process of modelling the firing effects – quite often corrected by means of adjusting coefficients.

The problematic aspects of describing the $r(p)$ function have been the subject of numerous works which analysed both the results of experimental pyrostatic testing using different ignition systems as well as theoretical models of the ignition process and propellant combustion. The results of investigation of ignition time and propellant combustion rate after ignition were presented in detail especially by Zel'dovich (1982), Assovskii *et al.* (1983, 1986) and Eisenrich *et al.* (2002). The modelling of thermal boundary layer due to igniter material flowing over a propellant surface was presented by Woodley *et al.* (2007). Some problems connected with the ignition process and unsteady combustion behaviour of smokeless propellants was mentioned and discussed by Khristenko (2001) and Khomenko and Shirokov (2006). The presented above problem was first discussed in Poland by Smoleński (1979) and examined by Torecki *et al.* (1997) and Papliński (2002).

The author of the hereby article had also joined these efforts by undertaking pyrostatic testing of propellants in non-standard loading conditions and with the use of non-standard ignition systems. The limitations with regard to the application of the linear form of the burning rate $r(p)$ were noted (2007, 2008). It was also shown that such a form, meaning $r = r_1 p$, may not be used directly as part of ballistic analysis of propellant systems, especially those making use of fine grain propellants.

The results of tests performed by Leciejewski and Surma (2011) within a conventional closed vessel (CCV) and within a micro closed vessel (MCV) indicated that for a propellant of a specific chemical composition and thickness of the combustible layer e_1, when using during the tests identical loading conditions but different ignition systems, it is possible to obtain different values of the r_1 coefficient for the linear $r(p)$ function as well as a different value of the dynamic characteristics of the propellant combustion process (relative quickness, dynamic vivacity).

The aim of the hereby paper is the analysis of the results from experimental closed vessel tests of a single base propellant characterized by:

a) varied thickness of the combustible layer (used during testing with identical loading conditions);

b) the same thickness of the combustible layer (while applying varied loading conditions during testing).

The same ignition system was used in both instances. The analysis performed should permit a more complete verification of the assumptions with regard to proper realization of the closed vessel comparative testing in the future.

2. Method and materials

The aim of work has been realized on the basis of closed vessel tests carried out inside a conventional closed vessel (CCV) with a volume of $W_0 = 200\,\mathrm{cm}^3$ and within a specialized closed vessel with a membrane safety valve (VCV – Vented Closed Vessel) described and used by Torecki *et al.* (1997), in which the interruption of the propellant burning takes place after the propellant gases reach a predetermined pressure level.

A black powder ballast with a mass of $\omega_{ign} = 2g$ was placed in a small sack made of a combustible material and used for igniting the propellant being subjected to testing. The ignition of the black powder was initiated by means of a thermal impulse emitted from the igniting head activated by an electrical impulse. During realization of the experiments, both the loading conditions as well as the pressure measuring system met the requirements of the standardization agreement STANAG 4115 (1997), used not only for industrial propellant testing but also commonly in the field of scientific tests.

The pressure was measured with a HPI 5QP 6000M piezoelectric transducer, whose signal was amplified by TA-3/D amplifier and recorded on a Keithley DAS-50 12-bit analog-to-digital converter at a frequency of 1 MHz. The maximum systematic error of the pressure indirect measurement system was 1.1%.

The subject of these tests constituted a single base propellant which varied mainly only in terms of its combustible layer thickness e_1 (half of web size). Single-perforation propellant grains were combusted in the CCV chamber, with a single determined loading density ($\Delta = 100\,\mathrm{kg/m}^3$) and the total web size thickness which equalled 0.33 mm, 0.37 mm and 1.52 mm respectively.

The average web size dimension of grains – declared by the manufacturer – was verified by direct measurements of groups of 150 granules using NEOPHOT 21 metallographic microscope and LUCIA software. Tests of this type have hereinafter been designated as A type tests.

The multi-perforation propellant grains with a constant combustible layer were burned in the VCV chamber (Fig. 1), but in the conditions of a broad range of loading densities ($\Delta = 75\text{-}700\,\mathrm{kg/m}^3$).

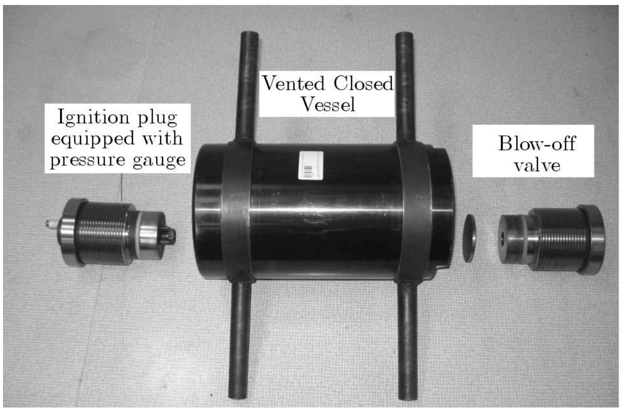

Fig. 1. Main parts of Vented Closed Vessel: combustion chamber (in the middle), ignition plug equipped with pressure gauge and blow-off valve

Tests of this type have in turn been designated as type B tests. Such an arrangement of the test program enabled evaluation of the influence of the propellant grain burning surface (in type A tests) as well as the loading density (in type B tests) on the dynamics of the burning process of the single base propellant, especially in its initial burning stage of the powder grains.

3. Results

In Fig. 2, the experimental changes of pressure p in time t, resulting from type A tests during combustion of the propellant with a mass ω_p, density ρ_p and containing N propellant grains with a perforation volume W_h are presented.

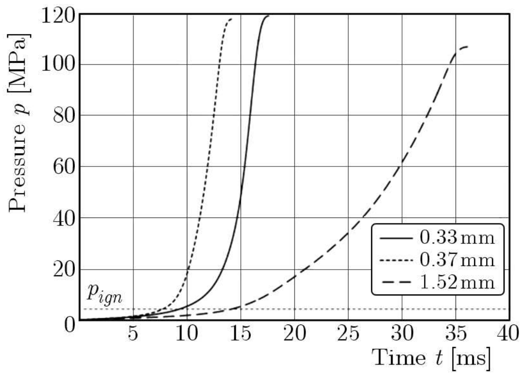

Fig. 2. Experimental plots of the function $p(t)$ resulting from combustion of the single base propellant with grains of different combustible layer values

Significant differences in time are observable between the time of the start of the black powder ignition (with energy characteristics: force f_{bp} and co-volume α_{bp}) until the time of the powder gases reaching the established ignition pressure p_{ign} resulting from the relation established by Serebryakov (1949)

$$p_{ign} = \frac{f_{bp}\omega_{bp}}{W_0 - \Big(\frac{\omega_p}{\rho_p} - NW_h\Big) - \alpha_{bp}\omega_{bp}} \tag{3.1}$$

The graphs of the rate of change of combustion $r(p)$ were calculated using the below formula

$$r = \frac{de}{dt} = \frac{de}{dz}\frac{dz}{dp}\frac{dp}{dt} \tag{3.2}$$

taking as the basis the registered experimental curves $p(t)$, while the method and the relations necessary for calculation of the variability in the thickness of the combustible layer with a change in the relative mass of propellant burnt (de/dz) as well as variability of the relative mass of the propellant burnt with a change in pressure (dz/dp) were assumed as described by Military Agency for Standardization in STANAG 4115 (1997). The $r(p)$ function curves are presented in Fig. 3.

From the calculations realized in accordance with relation (3.2) and Fig. 3, it results that the rate of combustion of the tested single base propellant is not identical within the initial combustion stage. Clearly observable are in this stage the differences in the combustion rate depending on the size of the propellant grains. It is possible after this stage to observe levelling of the burning rate values along with an increase of gas pressures within the combustion chamber.

The influence of intensity of the initial burn of propellant grains is also reflected during the determination of the coefficient r_1 for the linear form of the relation $r(p)$.

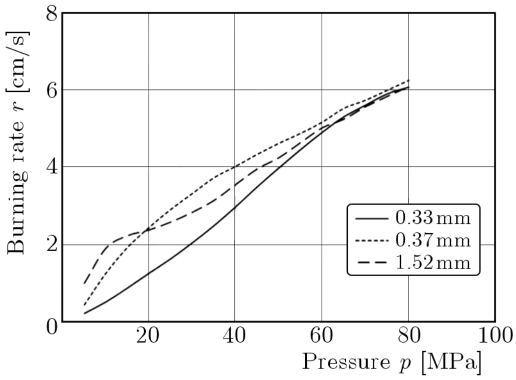

Fig. 3. The course of variability of the combustion rate $r(p)$ for the single base propellant with grains of different combustible layer thickness values

Its value may be established either on the basis of the total I_{pt} pressure impulse according to the relation below

$$r_1 = \frac{e_1}{I_{p_t}} = \frac{e_1}{\int\limits_{t_{p_{ign}}}^{t_{p_{max}}} p\,dt} \tag{3.3}$$

or on the basis of a limited pressure impulse I_{pa-b} according to the relation

$$r_1 = \frac{e_{a-b}}{I_{p_{a-b}}} = \frac{e_{a-b}}{\int\limits_{t_a}^{t_b} p\,dt} \tag{3.4}$$

Relation (3.3) takes into account the total course of the variability of gas pressure within the combustion chamber from the time of propellant ignition (from p_{ign} and $e = 0$) until the time of its complete combustion (meaning until p_{max} and $e = e_1$), while relation (3.4) eliminates from further calculations the period of initial burning (from $e = 0$ until the moment of the combustion of the layer $e = e_a$) and the afterburning (from the time of combustion of layer $e = e_b$ until complete combustion, meaning $e = e_1$) of the propellant grains.

The value of the coefficient r_1 calculated according to relation (3.3) is presented in Fig. 4a, while those calculated according to relation (3.4) are presented in Fig. 4b.

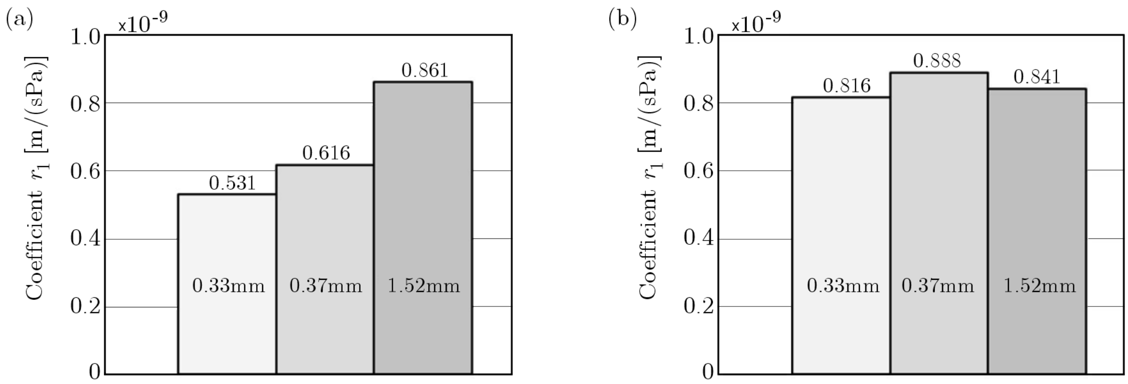

Fig. 4. Values of the coefficient r_1 for the single base propellant with grains of varied combustible layer thickness, calculated while taking into account the total pressure impulse: (a) the total pressure impulse – formula (3.3), (b) a limited pressure impulse – formula (3.4)

These figures indicate that the values of the coefficient r_1 calculated according to relation (3.3) may suggest significant differences in combustion rates of the tested propellant depending on the size of the propellant grains (thickness of the combustible layer e_1) which definitely contradicts the presentation of the coefficient r_1 calculated with the omission of the ignition time and after-burning time.

Type B tests permit the comparative analysis of the combustion rate, however only within a limited section of the z parameter. It is not possible for tests realized in such a manner to calculate the values of the coefficient r_1 from relation (3.3), in which the entire impulse of the propellant gas pressure is utilized while the possibility of comparing the values r_1 calculated according to relation (3.4) is very limited. Tests realized within the VCV chamber do however enable comparative analysis of the propellant burning rate calculated from relation (3.2) within the initial period of its combustion for different loading conditions (loading densities).

The diagrams illustrating the rate of change in combustion of the tested propellant in reference to the applied loading densities (75, 225 and 700 kg/m^3) are presented in Fig. 5.

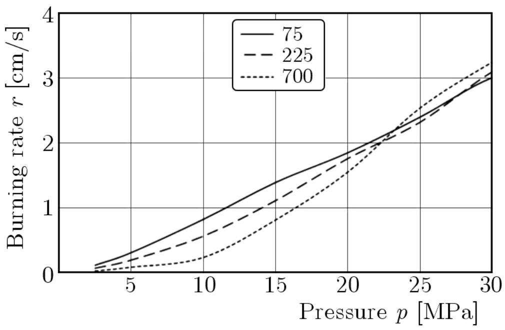

Fig. 5. The change of combustion rate $r(p)$ of the single base propellant (with grains of equal combustible layer e_1) depending on the loading densities applied in the tests

Distinctly visible are the discrepancies in the designated propellant combustion rate (in the initial stage of combustion) depending on the loading density, while maintaining the same ignition system.

4. Discussion

Taking into account the conclusions made by the author in previous papers, the results of tests in closed vessels at high loading densities published by Grune and Hensel (1993) and Wang (1993) as well as the results of tests and calculations realized for purposes of the hereby paper, valid becomes the statement that one of the fundamental assumptions of the geometric combustion model (established by Serebryakov (1949) and Corner (1950) in their fundamental works), which states that in the initial propellant combustion stage the ignition of the propellant is instantaneous and covers the entire accessible burning surface of the grains fails to function.

Such a state of affairs may present itself by obtaining from the pyrostatic (closed vessel) tests of different (depending on the loading and ignition conditions) coefficient values of the function $r(p)$ for the same propellant. This further results in:

- lack of basis for realization of proper comparative analysis of the propellant burning rate as a characteristic of the material,
- necessity of applying corrected values for the coefficients of the function $r(p)$ during analysis of the effectiveness of propellant systems (solving the main problem of internal ballistics).

A well founded basis exists to improve the above mentioned areas by applying a different approach to the conditions for realizing pyrostatic testing. In the case of realizing comparative tests of propellants (with the same test sample mass but of different propellant grain geometry or different chemical composition) combusted within a closed chamber of the same volume, establishing the conditions for experimental testing should be preceded by an analysis of the heat exchange conditions between gases of the igniting material (in the case of black powder, also of the hot solid particles) and varied surface of the propellant grains.

In accordance with the thermal model of ignition for solids, the decisive factor influencing the ignition of the solid state (propellant grain), is the generation of an appropriate area of temperature on its surface layer. The time for reaching such an area of temperature determined by Taylor *et al.* (2008) by the relation

$$t_{ign} \cong \frac{1}{4}\pi\lambda_p\rho_p c_{pp} T_{ppt}^2 t^2 S_p^2 Q_{ign}^{-2} \tag{4.1}$$

is a function of the material properties (density ρ_p, thermal conductivity λ_p, isobaric specific heat c_{pp}, thermal decomposition temperature T_{ppt}) and time t of the effective action of igniting gases energy Q_{ign} on the initial surface S_p of the propellant grains.

In order to establish the proper conditions for realization of pyrostatic comparative tests while taking into account technological difficulties (Cieślak *et al.*, 2011) associated with manufacturing of single base propellant grains of minimal surface coarseness (porosity) as well as repeatable shapes and sizes (pertaining especially to the fine grained single base propellant), relation (4.1) should include the real value of the grain surface area.

Attention to this problem was brought by Leonov (2008) where the relation for the burning rate of the porous single base propellant r_{por} was presented in the following form

$$r_{por} = r_0\frac{1}{1-\eta_0}(1+\mathit{\Delta}\overline{S}) \tag{4.2}$$

where r_0 is the burning rate of a nonporous single base propellant, η_0 – porosity of condensed phase, $\mathit{\Delta}\overline{S}$ – relative increase in the burning surface due to combustion in the pores.

The obtaining of proper values of the coefficients of the function $r(p)$ permitting direct application into simulation of propellant systems operation (without the requirement of corrective verification on the basis of realistic firing results) requires realization of pyrostatic tests, in which the possibility exists for application of loading and ignition system conditions similar to a real propellant system. Such possibilities may be provided by specialized MCV and VCV type manometric chambers.

It seems that all propellant grains are probably ignited uniformly, with all exposed surface areas of the grains performed by a gaseous ignition system presented by Jeunieau *et al.* (2002). The ignition mixture (for example CH_4-0_2) allows one to treat the ignition process of the propellant according to the geometrical model of propellant ignition and, additionally, to discriminate the combustion properties of two parts of the particles (in deterred propellants).

5. Conclusion

The experimental pyrostatic (closed vessel) tests still remain the fundamental method for determining the form of the function $r(p)$ and the value of its coefficients. The conditions of realization of such tests however, especially the method of ignition, should evolve in such a direction as to obtain more credible experimental data. The current approach to the issue of ignition during pyrostatic testing (established ignition mass and loading density) results in the fact that:

- in comparative tests of propellants with different chemical compositions or grain shape and size, the comparability of heat exchange conditions is entirely omitted,

- in identifying tests, realized for the purpos of propellant systems simulation, no possibility is being considered for the application of igniting systems found in real munitions.

The results of the experimental tests and theoretical analysis as well as literature information indicate that closed vessel tests should progress in the direction of "dedicated" tests, that is towards comparative tests where the ignition should take into account the principles of heat exchange, while the identification tests should incorporate the ignition systems similar to those found in real-life propellant systems. The specialized closed vessels of MCV and VCV type may prove a very useful tool in this aspect.

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