Comparative closed vessel tests – influence of ignition and loading conditions on propellant burning rate

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Abstract. *The most widely used experimental method to determine and to compare energetic and ballistic properties (force, co-volume, coefficients of burning rate law) of different propellants is burning a specific amount of propellant in a closed chamber.*
The procedure of determining the values of the individual material constants recommends similar conditions of closed vessel investigations like limited range of loading density and determined mass of black powder (igniter material) for determined loading density.
There also often occurs the need for performing of closed vessel comparative tests (carried out for two or more numbers of propellants), where one of them serves the role of a reference propellant and in relation to which described are the differences between the characteristics of the remaining propellants are described. Comparative tests of propellants should be understood to be such tests performed for identical loading conditions, including firstly the same closed chamber capacity, mass of the propellant burned (thereby the identical loading density) as well as identical ignition conditions which are understood as the same mass and the same type of igniter material.
In the present paper the influence of ignition and combustion conditions during closed vessel tests on possible deviations in determination of burning rate is analysed as a function of incident heat flux.

1. Introduction

The closed vessel tests of solid propellants are aimed mainly at the formulation of their energy and ballistic characteristics (force, co-volume, coefficients of burning rate law) treated as individual material constants. The procedure of determining the values of the individual material constants requires knowledge of the conditions of the realization of the experiment (loading conditions) such as the volume of the closed chamber, mass and type of propellant, which is subject to combustion in the closed chamber, geometric dimensions of its grains, mass, type and qualities of the material initializing the ignition of the propellant being tested, as well as information on the course of change (in time) of the propellant gas pressure generated from combustion of a set mass of the tested propellant.

There also often occurs the need for performing of closed vessel comparative tests (two or more numbers of propellants), where one of them serves the role of a reference propellant and in relation to which described are the differences between the characteristics of the remaining propellants. On the basis of many international and national regulations describing conditions of realization of comparative closed vessel tests it is concluded that the comparative tests of propellants should be understood to be such tests performed for identical loading conditions, including firstly the same closed chamber capacity, mass of the propellant burned (thereby the identical loading density) as well as identical ignition conditions which are understood as the same mass and the same type of igniter material.

2. Selected criteria of propellant ignition

The ignition of a propellant is a passing process leading to set it burn. Generally, the ignition comes down by supplying an appropriate dose of energy to the propellant's burning surface in order to generate such a chemical

and thermal state which would be equal to that of a constant burn. The ignition of a propellant grain is decided by the temperature of its external surface reached after time t_{ign} from the commencement of its heating with this time being dependent on the intensity of the heat exchange.

In reality the transfer of energy to the ignited surface of the propellant load being analysed from the ignition gasses takes place with the assistance of [1,2]:

-    free and forced convection,
-    radiation of hot ignition gasses and the red-hot solid particles of the igniter material,
-    collisions of the hot particles of the igniter material with the surface of the propellant being ignited,
-    the thermal conduction in places of contact between solid particles of the igniter material and the grains of propellant being ignited.

Significant in the solution is the unequivocal defining of the propellant ignition problem, which rests within the selection of criteria for propellant ignition. There is currently no single set definition of an ignition time and conditions describing it. In [3] defines the moment of ignition as the time, when the exchange of heat between gasses and the surface of the propellant will occur despite the fact that the delivery of the heat from an external source (primer) has been ceased. For this type of description of ignition time, the total heat released from the zone of the reaction must exceed the heat losses transferred from the reaction zone into the propellant volume and its heating which can be described as

$$\left[2 \cdot \lambda_{pr} \cdot \frac{R \cdot T_{ms}^2}{E_1} \cdot Q_1 k_{01} e^{\left(-\frac{E_1}{R \cdot T_{ms}} \right)} \right]^{0,5} \geq k^{\frac{1}{2}} \cdot \lambda_{pr} \cdot \frac{\delta T}{\delta x} \Big|_{x=x*} \tag{1}$$

where: λ_{pr} - thermal conductivity of the propellant; Q_1, k_{01}, E_1 – specific heat, pre-exponential coefficient, activation energy for the thermal sphere of decomposition reaction appropriately; R – universal gas constant; $T_{ms} = T(0,x)$ – maximum temperature of the propellant (surface); $x*$ - border of the cold layer of the chemical reaction zone, k – constant.

The mechanism of condition of heat in solid bodies is also a basis for the experimental and theoretical tests concerning of the magnitudes influencing ignition delay t_{ign}. In [4] the ignition delay (t_{ign}) is defined as the time from the start of igniter burning until the time at which the pressure reaches a value of 10% of the maximum pressure recorded in the closed-vessel experiment (Figure 1).
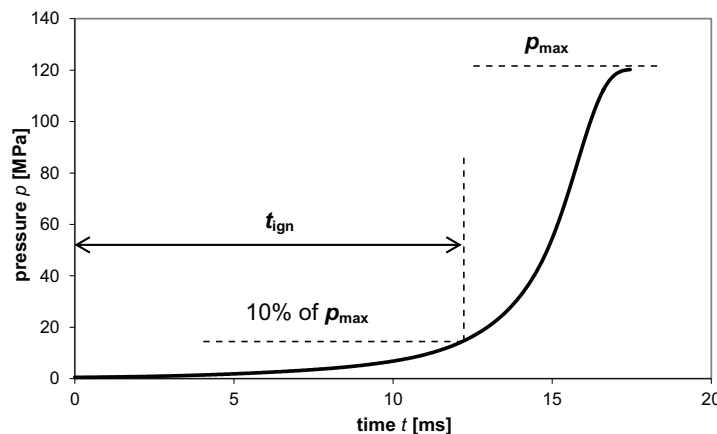

Fig. 1.   Example of a closed vessel test result, in which the ignition time (t_{ign}) is indicated

Ignition delay in [5] is defined as the dwell time between the ignition stimulus and the take-over of propellant combustion. The appropriate dependence

$$t_{ign} = \frac{1}{4} \cdot \pi \cdot \lambda_{pr} \cdot c_{pr} \cdot T_p^2 \cdot t^2 \cdot S^2 \cdot Q_i^{-2} \tag{2}$$

indicates that by describing the ignition delay, one should take into account the physical and chemical characteristics of propellant (heat conductivity λ_{pr}, specific heat c_{pr}, pyrolysis temperature T_p) and geometric characteristics (propellant surface area S) of the propellant grains as well as the conditions of interacting of igniting gasses on the propellant surface, meaning, the igniter energy Q_i transferred to the propellant and the time t of influence of this energy on an available initial propellant surface.

3. Comparative closed vessel tests

In the further part of the article presented are the results of closed vessel tests for which the subject of the experiment was single-base propellant. These tests focus on the determining the rate of burning of this propellant by creating different conditions for its ignition and loading (described further as type A, B and C tests).

Test group A included the combustion of single-base propellant (of equal propellant grain geometric dimensions and equal thickness of the combustible layer) in conditions of similar loading density but with different igniting systems. All tests were conducted at ambient temperature. The average web size dimension of grain (0.325 mm) - declared by manufacturer - was verified by direct measurements of groups of 150 granules using NEOPHOT 21 metallographic microscope and LUCIA software. Disposition of the web size dimension (20 % of (0.30 ÷ 0.31) mm, 60 % of (0.32 ÷ 0.33) mm, and 20 % of (0.34 ÷ 0.35) mm) confirmed manufacturer declaration.

Closed vessel investigations were carried out in two different vessels: conventional closed vessel (CCV) of 200 cm^3 and micro-closed vessel (MCV) of 1.786 cm^3. The MCV set was constructed on the basis of 7.62-mm machine gun barrel that was cut down to reduce the internal volume (Figure 2).
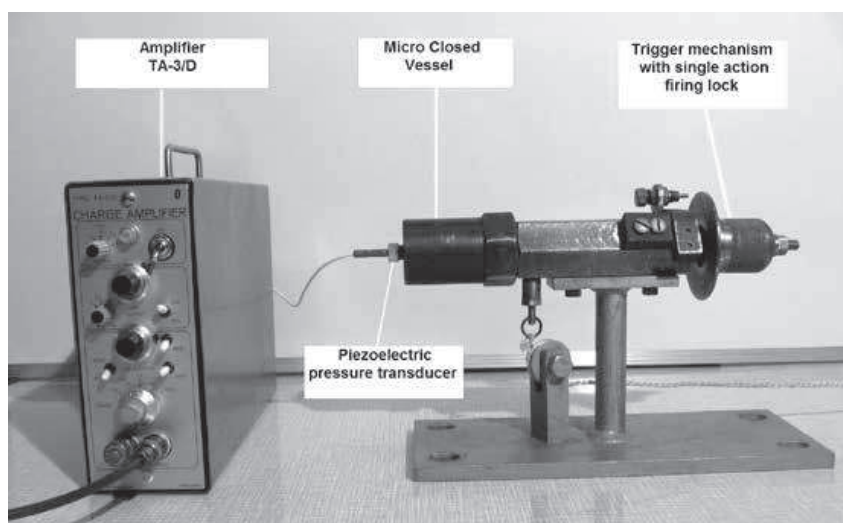

Fig. 2. Micro-Closed Vessel and measuring system of pressure

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. Maximum systematic error of pressure indirect measurement system was 1.1%. The ignition of the tested propellant was performed by three methods:

- A1 – black powder with a mass of 2 g in accordance with STANAG 4115 [6] requirements (the propellant being tested rests loosely on the side surface of the CCV set);
- A2 – black powder with a mass of 2 g, however both the black powder as well as the propellant being tested have both been places in the CCV in a container which is incinerated during the test (the remaining conditions are in accordance with STANAG 4115 requirements);
- A3 – the igniting material is in the form of a rifle cartridge percussion cap in the MCV set.

Selected characteristics of the pressure p graphs registered during the tests in the function of time t are presented in Table 1, while the change in combustion rate $r(p)$ after ignition is shown in Fig. 2. From the tests performed it occurs that a consequence of applying different conditions of ignition of the same propellant is the achievement

of significant differences in the maximum derivative of pressure, ignition time and dynamics of propellant combustion (burning rate). The value of burning rate can vary for the same value of pressure. For example, for pressure 80 MPa the burning rate varies from 6.04 cm s^{-1} to 7.04 cm s^{-1} depending on the used ignition method.

Table 1. Selected characteristics of p(t) graphs registered during the tests type A

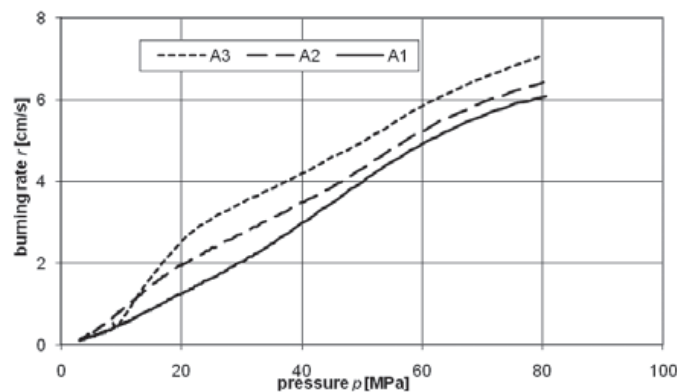| Method of ignition	Loading density [kg m^{-3}]	Maximum derivative of pressure $(dp/dt)_{max}$ [MPa ms^{-1}]	t_{pmax} [ms]	t_{ign} [ms]
A1		40.7	17.5	12.1
A2	100	45.9	14.3	10.1
A3		49.8	4.8	0.19

Fig. 3. Calculated rates of combustion $r(p)$ for type A tests

In tests designated with the symbol B, performed in accordance with the STANAG 4115 requirements, single-base propellant was subjected to combustion in the CCV (in conditions of uniform loading density and equal mass of black powder used as igniting material) with identical propellant grain shape, varying however in the thickness of the combustible layer (web size): 0.33 mm (B1), 0.37 mm (B2) i 1.52 mm (B3).
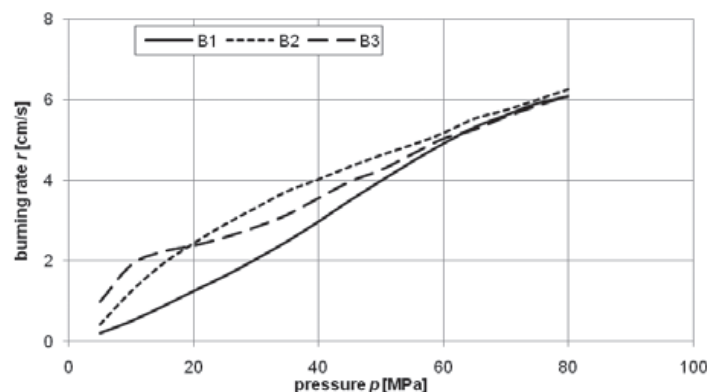

Fig. 4. Calculated burning rage $r(p)$ for type B tests

Figure 4 represents the change in combustion rate after ignition. Interesting is that directly after ignition, strong differences in burning rate are observed. With increase in time the combustion is close to that existing in stationary period at the specified pressure.

During the type C tests, a single-base propellant was used (with uniform propellant grain shape) ignited by the same mass of the same igniting material but was combusted in conditions of significant differences in the loading density: 75 kg m^{-3} (C1), 225 kg m^{-3} (C2) and 700 kg m^{-3} (C3).
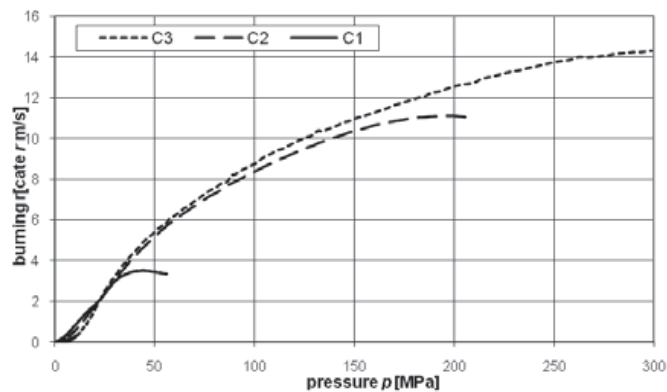
Fig. 5.   Calculated burning rates $r(p)$ for type C tests

Tests C1 and C2 were performed in the CCV while C3 tests in a chamber equipped with a diaphragm safety valve (Vented Closed Vessel) [8]. The calculated burning rates $r(p)$ are presented in Fig. 5 and 6. There are observed similar effects (in comparison with type B tests) in differences of burning rate directly after ignition.
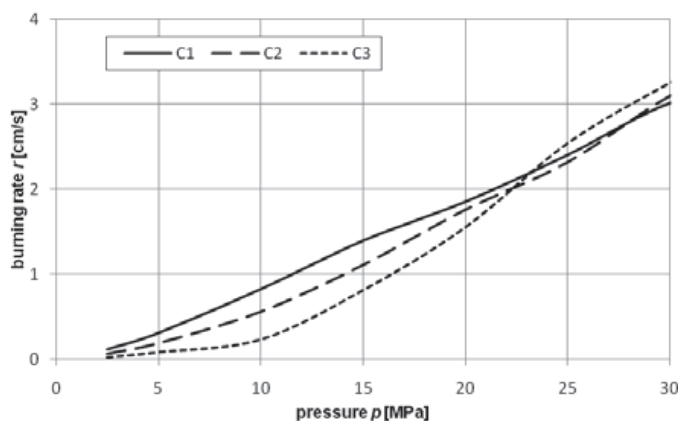

Fig. 6.   Calculated burning rates $r(p)$ for the initial stage of combustion (type C tests)

It has been established experimentally that dynamic characteristics of combustion of tested propellant depend on ignition conditions during closed vessel investigation. It means that coefficients of the burning rate law (linear [9] or exponential [10]) as well as absolute quickness AQ may have different values if closed vessel tests for the same propellant are performed with different ignition systems or different loading conditions.

On the basis of results from the experimental tests performed and theoretical analysis of the burning rates for different conditions of ignition and loading, it appears that great difficulty is presented, as was stated in *Introduction*, of the establishing of identical conditions of comparative tests, especially in the context of:

- geometric assumptions of the burning model [2,9,10], especially the assumptions that the ignition of the given propellant is instantaneous over the entire available combustible surface of its grains;

- the heat exchange process between gas and solid particles generated as a result of the burning of black powder (igniting material) and the surface of the tested propellant grains.

As a general rule, comparative tests concern testing of propellants not only different in chemical composition but also of different shapes and dimensions of the propellant grains. Justified is therefore the question whether the uniform conditions of the closed vessel comparative tests are those described in i.e. MIL-STD 286B [11] or in the STANAG 4115, or whether individual ignition conditions should be established for each propellant but comparable from the point of view of the heat exchange process.

With regard to the energy characteristics such as the force as well as the co-volume established in the above documents, the conditions of the tests do not have (as a result of the determining of the global effect of the energy release process) a greater influence on the designation of their values.

A much more significant problem is posed by the precise designation of the burning rate (coefficients of the burning rate law).

4. Conclusions

Discussing the comparative tests of different propellants, it is important to formulate the conditions in such manner as to unequivocally isolate their comparativeness. A thesis may be stated for that identical loading conditions (Δ=idem) of propellants (with an identical or different chemical composition) containing grains of different shapes and sizes as well as an identical mass of black powder used for its ignition do not constitute a comparison of the dynamic characteristics of burning for these propellants.

The ignition of a propellant grain is decided by the temperature of its external surface reached after time t_{ign} from the initial moment of the heating process, and this time is dependent on the intensity of the heat exchange. As a result of the different intensity of the heat exchange the external surface (of a specific thickness) is subject to the formation of a specific gradient of temperature. The formation of a specific temperature gradient in the comparative tests of propellants with the same chemical composition and propellant grains of the same shape and size (identical burning surfaces) may be a result of applying of the same mass of black powder (that generate during burning the heat stream of an identical value).

In the case of comparative tests of propellants with different chemical composition and containing grains where the total initial burning surface is different (for the same mass of propellant), for the time of the ignition, aside from the magnitudes stipulated in (10), in the case of using black powder as the igniting material, influence will be in the form of an active number of hot solid primer particles per unit of available area of propellant grains.

The issues addressed in the hereby article concerns an unequivocal determination of the burning rate (especially in the initial period of the ignition of propellant grains) and thereby the values of coefficient of the burn rate law was a basis for determining a specific method [8] determining the mass fraction burning rate of the propellant. This method does not require the need to make use of assumptions of the geometric burning model and it is not required to determine the state of the burning rate law for a specific propellant.

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