PROBLEMY MECHATRONIKI
UZBROJENIE, LOTNICTWO, INŻYNIERIA BEZPIECZEŃSTWA

ISSN 2081-5891
E-ISSN 2720-5266

13, 4 (50), 2022, 9-22

PROBLEMS OF MECHATRONICS
ARMAMENT, AVIATION, SAFETY ENGINEERING

Theoretical and Experimental Research on Gun Propellant Burning

Gabriel F. NOJA[1*], Adrian N. ROTARIU[2], Marius I. MĂRMUREANU[1], Adrian MALCIU[1], Bogdan G. PULPEA[2], Florin M. DÎRLOMAN[2]

[1]*Centre for Research and Innovation for Armament,*
Military Equipment and Technologies Research Agency, Bucharest, Romania
16 Aeroportului, Str., Clinceni, 077025 Ilfov, Romania
[2]*Military Technical Academy „Ferdinand I",*
39-49 George Cosbuc Avenue, District 5, 050141 Bucharest, Romania
[*]*Corresponding author's e-mail address and ORCID*:
gnoja@acttm.ro; https://orcid.org/0000-0002-4358-5761

Received: July 21, 2022 / Revised: August 16, 2022 / Accepted: August 18, 2022/
Published: December 30, 2022.

DOI 10.5604/01.3001.0016.1453

Abstract. The paper presents a method to determine the burning rate law and the progressivity coefficient of the fine-grained propellants shape. To achieve the objective of this paper, a series of tests were performed in a closed vessel. The results obtained from these tests were processed to determine experimentally the burning rate and the progressivity coefficient of the propellant shape starting from the premise that the burning surface has identical values for the same value of the volume fraction of burned propellant in two closed vessel tests at different loading densities.

The experimental determination of the progressivity coefficient of the propellant shape shows that irregularities of the shape of the fine-grained propellants and gradual ignition lead to values completely different from the theoretical ones.

Keywords: interior ballistic, closed vessel, gun propellant, burning rate, progressivity coefficient of the propellant shape

1. INTRODUCTION

Due to the continuous need to develop and improve the performance of weapons systems, over the time, there has been a continuing concern of the research community to determine the ballistic characteristics of propellants for the numerical models of interior ballistics to be as close as possible to the physical model of the firing phenomenon [1-4], thus developing algorithms for processing the data obtained by performing closed vessel tests [5-6].

In concordance with the provisions from STANAG 4115, following the tests performed in the closed vessel, the propellant impetus, propellant covolume, burning rate, and the progressivity coefficient of the propellant shape can be determined [7]. The propellant burning rate and its characteristics represent the basic elements used in the computational model which predicts the behaviour of the interior ballistics phenomenon. In order for the numerical models of interior ballistics to be as close as possible to the physical model of the firing phenomenon, these characteristics must be determined as accurately as possible. R. Trębinski et al., in their paper, showed that increasing the amount of black powder igniter loads leads to major deviations in order to determine the burning rate and vivacity of the propellant because the ignition of the tested propellant grains starts before reaching the nominal ignition pressure [8]. Three years later, in their study, to determine the burning rate and vivacity of fine-grained propellants, by the algorithm used, they showed that there is considerable difference between theoretical and experimental results due to irregularities of the propellant shape, the appearance of cracks on their surface, and the preheating of the outer layer of the propellant grain before the combustion starts [9].

The standard methods of interpreting the results obtained after performing the close vessel tests, as described in the literature [10-11], give us satisfactory results in determining the burning rate and vivacity of the gun propellants, but only for coarse-grained propellants with regular shapes of grains. In the case of fine-grained propellants, the standard method does not provide satisfactory results because these propellants have major shape deviations. Therefore, in this paper, the approach is to determine the burning rate and the progressivity coefficient of the propellant shape experimentally starting from the hypothesis that for two tests performed in the closed vessel, the burning surface has identical values for the same value of the volume fraction of burned propellant without taking into account the heat losses because they do not significantly affect the results.

In the same sense, knowing that the use of a large igniter load leads to erroneous results [8], the tests were performed without black powder igniter, and the testing load being closed in a plastic bag and arranged around the head of the electrical igniter.

2. MATERIALS AND METHODS

2.1. Theory

Noble and Vieille were the first researchers to perform closed vessel tests in order to observe the ballistic behaviour of propellants [12]. At the base of the proposed algorithm for determining the ballistic characteristics of the propellant is Noble and Abel's equation of state of the gases resulting from the burning of the propellant in the closed vessel:

$$P_{max} = \frac{f \cdot \Delta}{1 - \alpha \cdot \Delta} \tag{1}$$

where: $P_{\max}$ – is the maximum pressure,

f – the propellant impetus,

Δ – the loading density,

α – the propellant covolume.

Considering that the propellant impetus and the propellant covolume are constant in relation to the loading density and the maximum pressure, obtained after performing the closed vessel tests, and using the equation of Noble and Abel which expresses the dependence between maximum pressure and loading density leads to relations based on which the impetus and the propellant covolume can be determined from the two closed vessel tests at two different loading densities.

$$\alpha = \frac{\frac{P_{max\,2}}{\Delta_2} - \frac{P_{max\,1}}{\Delta_1}}{P_{max\,2} - P_{max\,1}} \tag{2}$$

$$f = \frac{P_{max\,2}}{\Delta_2} \cdot (1 - \alpha \cdot \Delta_2) = \frac{P_{max\,1}}{\Delta_1} \cdot (1 - \alpha \cdot \Delta_2) \tag{3}$$

Based on the general formula of pyrostatics [13], after burning the volume fraction of propellant, ψ in the closed volume, W_0 links the resulting pressure p from the propellant charge ω, the solid propellant density δ, the propellant impetus f, and the propellant covolume α.

$$p = \frac{f \omega \psi}{W_0 - \frac{\omega}{\delta}(1 - \psi) - \alpha \omega \psi} \tag{4}$$

Starting from the general formula of pyrostatics and rewriting it in an advantageous form, the relation for the volume fraction of burned propellant was obtained according to the loading density, solid propellant density, pressure of the propellant gases, propellant impetus, and the propellant covolume, under the following form:

$$\psi(t) = \frac{\frac{1}{\Delta} - \frac{1}{\delta}}{\frac{f}{p(t)} + \alpha - \frac{1}{\delta}} \tag{5}$$

Knowing the variation in time of the volume fraction of burned propellant, obtained experimentally, the propellant gases rate generation, $d\psi/dt$ can be determined. The burning rate law gives the link between the burning rate and pressure. There are several empirical relations for the burning rate, but the most used is the relation proposed by Saint Robert. Thus, considering that throughout the entire pressure range we can use the law of burning rate,

$$u = A \cdot p^{\upsilon} \tag{6}$$

where: A – the burning rate coefficient,

υ – the exponential coefficient of the burning rate has constant values.

The theoretical deductions allow us to obtain a connection between variation in time of the volume fraction of burned propellant and the burning rate [13]

$$\frac{d\psi}{dt} = \frac{S}{\Lambda_0} A p^{\upsilon} \tag{7}$$

where: S – is the current burning surface of the propellant grain,

Λ_0 – is the initial volume of propellant grain.

Considering that for the two performed closed vessel tests, the combustion surface within the two tests has identical values for the same value of the volume fraction of burned propellant ψ, then for any value of ψ we have the equality:

$$\frac{\left(\frac{d\psi}{dt}\right)_{\Delta_1}}{\left(\frac{d\psi}{dt}\right)_{\Delta_2}} = \frac{\frac{S}{\Lambda_0} A {p_{\Delta_1}}^{\upsilon}}{\frac{S}{\Lambda_0} A {p_{\Delta_2}}^{\upsilon}} = \left(\frac{p_{\Delta_1}}{p_{\Delta_2}}\right)^{\upsilon} \tag{8}$$

So, the “local” value of the exponential coefficient of the burning rate is calculated with the relation:

$$\upsilon = \frac{\ln\left(\left(\frac{d\psi}{dt}\right)_{\Delta_1}\right) - \ln\left(\left(\frac{d\psi}{dt}\right)_{\Delta_2}\right)}{\ln\left(p_{\Delta_1}\right) - \ln\left(p_{\Delta_2}\right)} \tag{9}$$

It is expected that the „local” value will not be constant over the entire range of variation of the volume fraction ψ, but a global value can be obtained through a mediation of fluctuations.

After determining a global value for the exponential coefficient of burning rate law, the coefficient of burning rate law A is calculated based on the formula:

$$A = \frac{e_1}{\int_0^{t_{k2}} {p_{\Delta_2}}^{\nu} dt} \tag{10}$$

In determination of the characteristics of the burning rate by the algorithm presented above, no condition is imposed on the evolution of the burning surface or the volume fraction of burned propellant as a function of the relative burned propellant thickness, z. Therefore, based on the experimental data knowing for each moment the values of $\psi(t)$, a relation of the progressivity coefficient of the propellant shape can be obtained depending on the volume fraction of burned propellant, $\sigma(t)$:

$$\sigma(\psi) = \frac{d\psi}{dt} \cdot \frac{\Lambda_0}{S_0} \cdot \frac{1}{A \cdot p^{\nu}} \tag{11}$$

2.2. Experimental tests and materials

In order to evaluate the ballistic characteristics of the non-phlegmatized, VT mark propellant, square plate type (Fig.1), tests were performed in the OZM closed vessel [11], with an interior volume of the chamber of 40 cm^3 (Fig. 2), from the endowment of the Military Technical Academy „Ferdinand I” (Bucharest, Romania).

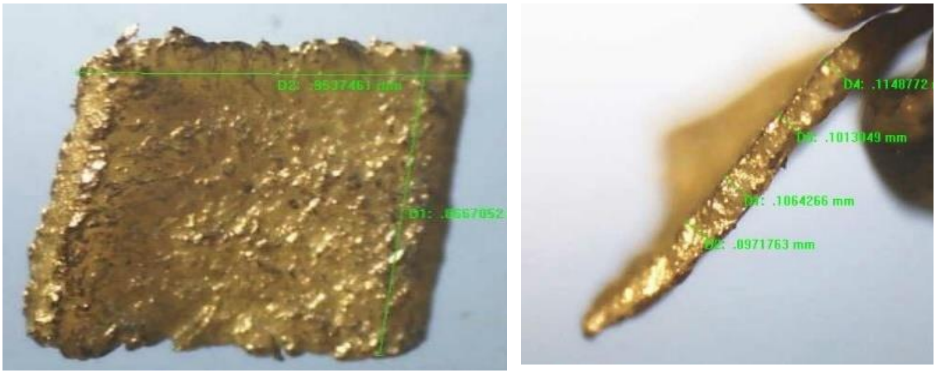

Fig. 1. VT mark propellant grain, square plate type observed and measured under a microscope

For performing the two closed vessel tests, propellant charges of 6 g and 8 g were used, which led to obtaining loading densities of 0.15 g/cm^3, and 0.20 g/cm^3, respectively.

The closed vessel has been equipped with a piezoelectric pressure transducer, mounted in an adapter with a minimum frequency response of 25 kHz, which allows us a measurement with a maximum error of +/- 0.1% and a MB-2N electrical igniter. The tests were performed at the room temperature of +20°C.

Fig. 2. System configuration: 1 – closed vessel body; 2 – locker; 3 – closed vessel cap; 4 – propellant charge; 5 – exhaust valve; 6 – electrical terminals for firing; 7 – pressure transducer; and 8 – fastening system.

3. RESULTS AND DISCUSSION

Following the performance of the two tests in the closed vessel at different loading densities, the variation in time of the pressure was recorded by means of the pressure transducer and the PicoScope data acquisition system (Fig. 3 and Fig. 4).

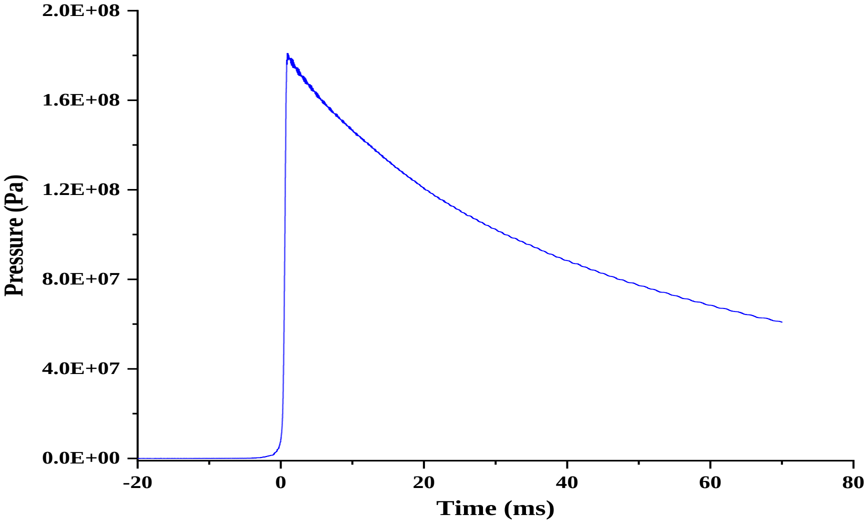

Fig. 3. Recorded signal for the loading density 0.15 g/cm^3

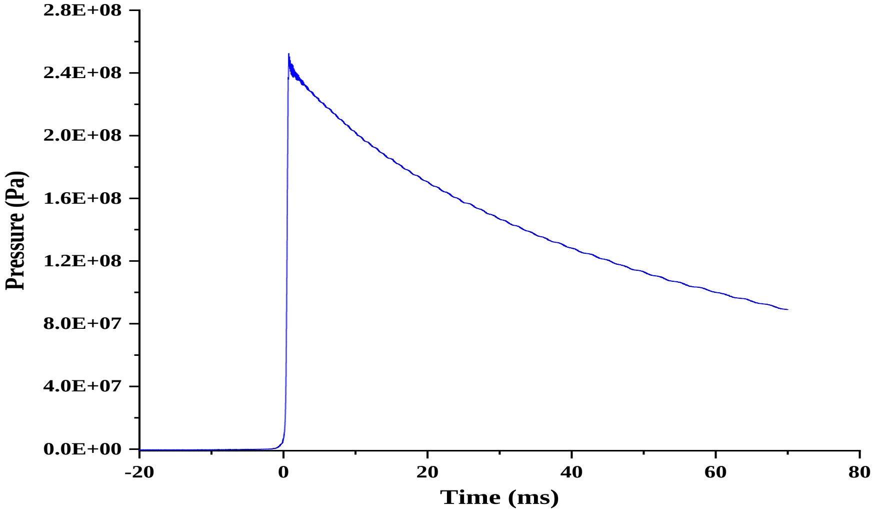

Fig. 4. Recorded signal for the loading density 0.20 g/cm^3

Since the recorded pressure curves had small oscillations caused by noise, they were imported into the MATLAB software, in which a smoothing was performed by calling a smoothing spline function (a smoothing parameter of 0.98 was used) – Fig. 5 and Fig. 6.

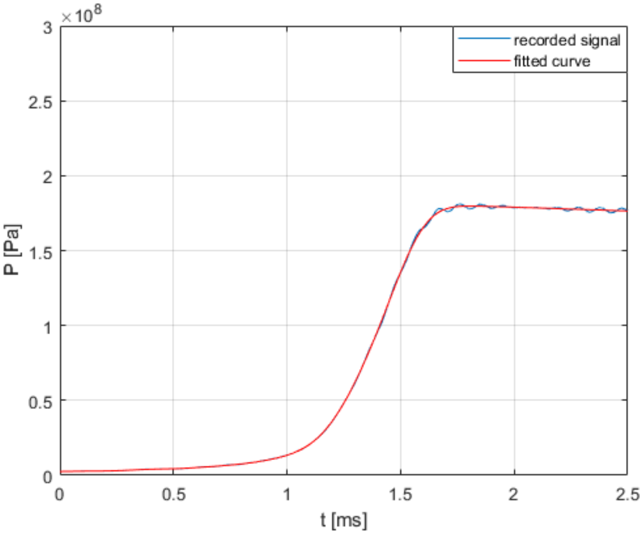

Fig. 5. Graph of the smoothed pressure curve as a function of time for the loading density Δ_1

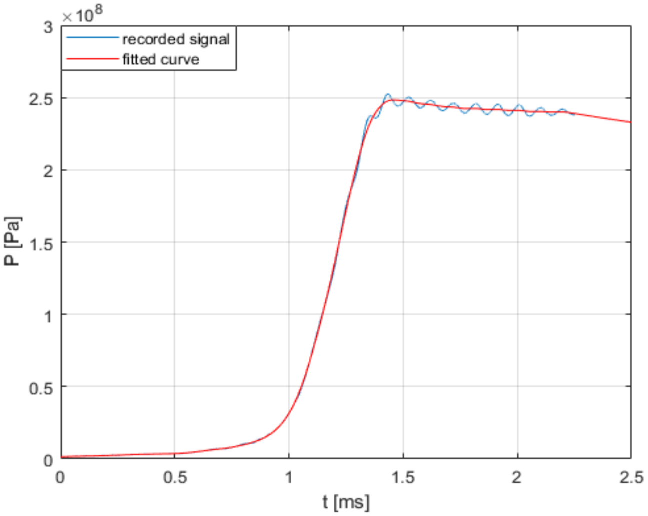

Fig. 6. Graph of the smoothed pressure curve as a function of time for the loading density Δ_1

After smoothing the curves, the obtained values for the maximum pressure $P_{\max\Delta 1}$ = 181.2 MPa and $P_{\max\Delta 2}$ = 251.7 MPa were used in formulas (2) and (3) to calculate the value for the propellant impetus and the propellant covolume:

$$f = 1.0870 \cdot 10^6 \text{ [J/kg] and } \alpha = 0.61194 \cdot 10^{-3} \text{ [m}^3\text{/kg]}$$

Using relation (5), that links the volume fraction of burned propellant and the pressure of the propellant gases, leads to the time variation of the volume fraction of burned propellant for the two tests performed in the closed vessel (Fig. 7).

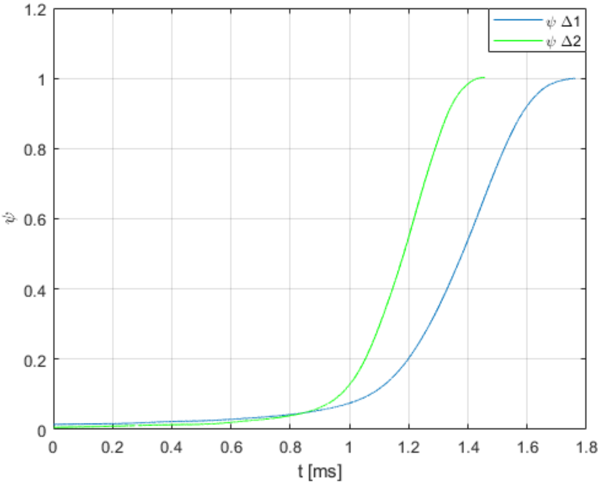

Fig. 7. Graph of the evolution in time of the volume fraction of burned propellant at the two loading densities

Determining the propellant gases rate generation by the derivation in relation to time of the volume fraction of burned propellant and starting from the premise that the burning surface for the two tests performed has identical values for the same value of the volume fraction of burned propellant lead to the experimental determination of the burning rate law, by finding the exponential coefficient of combustion using formula (9) – Fig. 8.

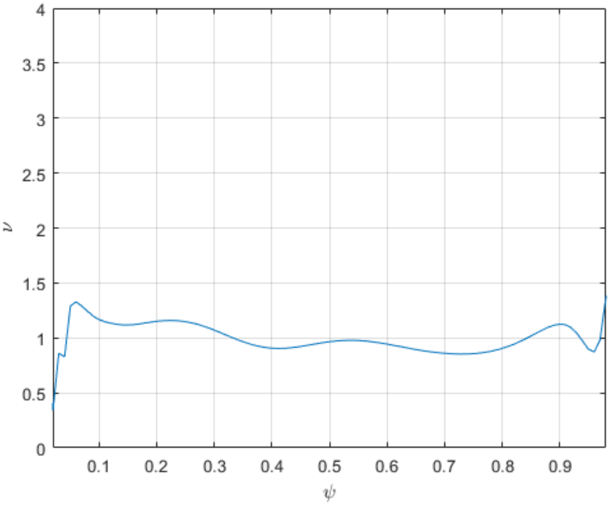

Fig. 8. The exponential coefficient of the burning rate law as a function of the volume fraction of burned propellant

Based on the presented graphic, in which the exponential coefficient of burning is materialized in relation to the volume fraction of burned propellant, it is observed that its value over the entire interval is approximately equal to unity. At the same time, a significant deviation from this value can be observed at the beginning of the burning process, when the pressure value is low because in the closed vessel tests there was not used a black powder igniter.

After determining the exponential coefficient of burning rate law, according to the presented algorithm, the coefficient of combustion rate *A* can be determined using relation (10) and the burning rate of the propellant with relation (6).

According to our approach, for determination of the burning rate law no condition was imposed regarding the evolution of the burning surface, *S* or of the volume fraction of burned propellant, ψ depending on the relative burned propellant thickness, *z* and knowing the evolution in time of the volume fraction of burned propellant, $\psi(t)$ allowed us determination of the progressivity coefficient of the propellant shape according to relation (11) – Fig. 9.

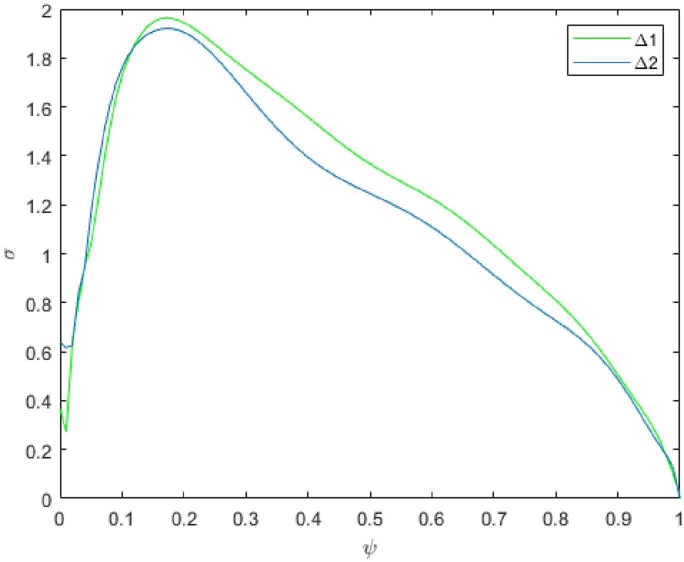

Fig. 9. Evolution of the experimental progressivity coefficient of the propellant shape for the two loading densities

Based on Fig. 9, the evolution of the curve that materialized experimental progressivity coefficient of the propellant shape in relation to the volume fraction of burned propellant shows us that this propellant mark has a strongly progressive burning in the range of ψ = [0 – 0.25], after which it is characterized by a degressive burning.

Knowing from the literature [12], that the propellants with a square plate type geometry have a neutral burning lead to determination of the theoretical progressivity coefficient of the propellant shape in order to observe the differences between its theoretical and experimental values.

3.1. Theoretical determination of the shape coefficients of the propellant grain

The determination of the theoretical curve of the progressivity coefficient of the propellant shape, as presented in the literature [12], is done according to the shape coefficients of the propellant grain based on theoretical formulas:

$$\begin{cases} \chi = 1 + \alpha' + \beta' \\ \lambda = \dfrac{\alpha' + \beta' + \alpha'\beta'}{1 + \alpha' + \beta'} \\ \mu = \dfrac{\alpha' \cdot \beta'}{1 + \alpha' + \beta'} \end{cases} \tag{12}$$

where $\alpha' = e_1/b$ and $\beta' = e_1/c$.

In order to determine the overall dimensions of the propellant grains, 20 samples of propellant grains were inspected under a microscope, followed by the calculation of the average values, thus obtaining:

- grain thickness $2e_1 = 0.136807$ mm;
- grain length $2c = 1.050185$ mm;
- grain width $2b = 0.938930$ mm.

Applying formulas (11) for determination of the shape coefficients of the propellant grains there will be obtained:

$$\kappa = 1.275975$$
$$\lambda = -0.23116$$
$$\mu = 0.018627$$

Determining the theoretical shape coefficients of the propellant grain led to the theoretical determination of the progressivity coefficient of the propellant shape based on the following relation [13]:

$$\sigma = 1 + 2\,\lambda z + 3\,\mu z^2 \tag{13}$$

where: z – the relative burned propellant thickness ($z = e/e_1$),
e – the burned propellant thickness, ($e = A \cdot \int_0^{t_{k_2}} p^{\nu}\, dt$).

As it can be seen in the graph, shown in Fig. 10, the curve of the progressivity coefficient of the propellant shape determined theoretically has a major deviation from the curve obtained experimentally. This deviation occurs due to the fact that the shape coefficients take into account only the geometry of the propellant grains.

At the same time, from a geometric point of view, the real propellant grains show major deviations from the ideal shape and dimensions and on their surface, there are cracks that lead to the modification of the theoretical burning surface.

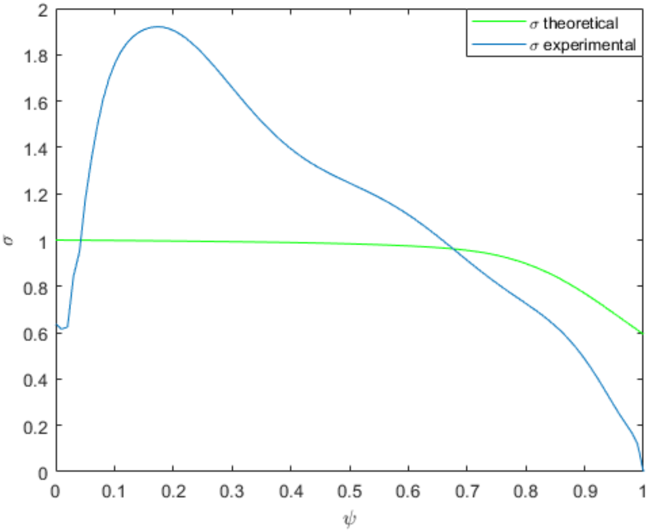

Fig. 10. The difference between the evolution of the theoretical progressivity coefficient of the propellant shape and the experimental one

On the other hand, analysing the curve of the theoretical coefficient of progressivity, it can be observed that its initial value is equal to unity, thus highlighting the simplified hypothesis according to which the ignition of the propellant charge is instantaneous throughout its mass and the entire surface of the propellant grain. In the same sense, analysing the evolution of the experimental curve, it can be seen that its initial value differs from the unity, highlighting the fact that in reality the ignition of the propellant charge is done gradually, not instantly.

4. CONCLUSIONS

1. Using the burning rate law, proposed by Saint Robert, and determining the burning rate coefficients, based on the premise that the burning surface has identical values for the same value of the volume fraction of burned propellant in two closed vessel tests at different loading densities, provides repetitive results that led to the validation of the premise.
2. The deviations of the real propellant grain shape from the ideal shape, the prolonged process of ignition, and the presence of cracks on their surface lead to variation in time of the burning surface and implicitly to the variation of the progressivity coefficient of the propellant shape, thus for the study of the ballistic behaviour of fine-grained propellants the theoretical methods lead to erroneous values.

3. The ascending part of the experimental progressivity coefficient of the propellant shape corresponds to the ignition process so, a prolonged process of ignition led to major differences between the experimental and theoretical coefficients.
4. In order for the numerical models of interior ballistics to be as close as possible to the physical phenomenon of firing, the theoretical progressivity coefficient of the propellant shape must be recalculated. Using the reverse engineering method, based on the experimental progressivity coefficient of the propellant shape, two new sets of values can be determined for the shape coefficients of the propellant grain, the first one during the progressive burning and the second one during the degressive burning.

FUNDING

This work was supported by a grant of the Ministry of Research, Innovation and Digitization (in Romania), CNCS/CCCDI – UEFISCDI, project number PN-III-P2-2.1-PED2021-1890, within PNCDI III.

REFERENCES

[1] Tırak, Ergun, Mohammed Moniruzzaman, Ercan Degirmenci, and Amer Hameed. 2019. „Closed vessel burning behaviour and ballistic properties of artificially degraded spherical double-base propellants stabilized with diphenylamine”. *Thermochimica Acta* 680 : 178347-1-9.

[2] Rotariu, Adrian-Nicolae, Liviu Matache, Florina Bucur, Marius Cîrmaci-Matei, Marius Mărmureanu, and Eugen Trană. 2020. „Implementation of a gumbel distribution function in interior ballistic calculations for deterred propellants”. *U.P.B. Sci. Bull., Series B* 82 (1).

[3] Carlucci, E. Donald, and Sidney S. Jacobson. 2008. *Ballistics. In Theory and Design of Guns and Ammunition*. USA, Boca Raton, FL: CRC Press.

[4] Degirmenci, Encar. 2015. „Effects of grain size and temperature of double base solid propellants on internal ballistics performance”. *Fuel* 146 : 95-102.

[5] Price, C., and Arpad A. Juhasz. 1977. „Versatile User-Oriented Closed Bomb Data Reduction Program (CBRED)”, BRL-Report-2018. US Army Ballistic Research Laboratory, Aberdeen Proving Ground, USA.

[6] Homan, E. Barrie, and Arpad A. Juhasz. 2001. „XLCB: A New Closed-Bomb Data Acquisition and Reduction Program”, Army Research Laboratory, ARL-TR-2491.

[7] STANAG 4115. “Definition and Determination of Ballistic Properties of Gun Propellants” (2nd ed.). 1997. Belgium, Brussels: Military Agency for Standardization.

[8] Trębiński, Radosław, Zbigniew Leciejewski, and Zbigniew Surma. 2018. Investigations of the influence of ignition on dynamic vivacity of propellants. In *Proceedings of the 12th International Armament Conference on Scientific Aspects of Armament & Safety Technology*. Poland, Jachranka, September 17-20, 2018.

[9] Trębiński, Radosław, Zbigniew Leciejewski, and Zbigniew Surma. 2022. „Determining the burning rate of fine-grained propellants in closed vessel test”. *Energies* 15 (7) : 2680-1-14.

[10] Corner, J. 1950. *Theory of the Interior Ballistics of Guns*. USA, New York, NY: John Wiley.

[11] Goga, D.A. 2007. PO-LTECAM-15, *Procedură operaţională pentru Determinarea caracteristicilor balistice ale pulberilor prin trageri în bombele balistice la volum constant* (Ediţia 1). ATM, 25.10.2007.

[12] Vasile, Titică. 1993. *Balistica interioară a gurilor de foc* (volumul I), Bucureşti: Editura Academiei Tehnice Militare.

[13] Serebryakov, M.E. 1962. *Interior Ballistics of Tube Weapons and Solid Fuel Rockets*. Moscow: State Scientific and Technical Publishing House Oborongiz.