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Preliminary analysis of ballistic requirements for LOVA propellants for new generation tank ammunition
Wstępne analizy wymagań balistycznych prochów LOVA do amunicji czołgowej nowej generacji

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Abstract: At the end of 2016, the Scientific-Industrial Consortium (Mesko S.A., Polska Grupa Zbrojeniowa S.A., Warsaw University of Technology, Military University of Technology, Military Institute of Armament Technology) set up an R&D project to develop and manufacture a demonstrator of new generation critical components for a 120 mm Polish tank munition. The critical elements for the project included a combustible charge case, an insensitive propellant and tungsten rods for sub-calibre projectiles. The task of the Military University of Technology was to develop the basic technology and fabricate insensitive LOVA propellants on a laboratory scale (research team of the Faculty of Advanced Technologies and Chemistry) and carry out the ballistic and simulation tests of a 120 mm tank gun using ammunition incorporating the developed LOVA propellant (research team of the Faculty of Mechatronics, Armamen and Aerospace).
The article also includes an analysis of available literature on energy and ballistic properties of LOVA and JA-2 propellants. Closed-vessel tests of JA-2 propellant (manufactured by Nitrochemie AG, designation LO5460) were also carried out. The tests were carried out in a 200 cm³ closed vessel. Based on the propellant gas pressure/time records, the propellant force and co-volume, and dynamic vivacity curves were determined. A linear combustion rate coefficient was determined using the measured results of the propellant grain geometry. The authors' own data enabled the carrying out of preliminary simulation tests of the 120 mm propellant system.

Streszczenie: Pod koniec 2016 r. Konsorcjum Naukowo-Przemysłowe (Mesko S.A., Polska Grupa Zbrojeniowa S.A., Politechnika Warszawska, Wojskowa Akademia Techniczna, Wojskowy Instytut Techniczny Uzbrojenia) rozpoczęło realizację projektu badawczo-rozwojowego, którego celem jest opracowanie i wykonanie demonstratorów technologii krytycznych elementów do nowej generacji, polskiej amunicji czołgowej 120 mm. Do elementów krytycznych w tym projekcie zaliczono samospalającą się łuskę, małowrażliwy materiał miotający oraz pręty wolframowe do pocisku podkalibrowego. Zadaniem Wojskowej Akademii Technicznej jest opracowanie podstaw technologii i wykonanie w skali laboratoryjnej małowrażliwego materiału miotającego typu LOVA (zespół badawczy Wydziału Nowych Technologii i Chemii) oraz przeprowadzenia badań balistycznych i badań symulacyjnych zjawiska strzału w 120 mm czołgowym układzie miotającym z wykorzystaniem

amunicji elaborowanej opracowanym prochem LOVA (zespół badawczy Wydziału Mechatroniki, Uzbrojenia i Lotnictwa).

W niniejszym artykule zawarto analizy literaturowe dotyczące właściwości energetyczno-balistycznych prochów typu LOVA oraz prochu JA-2. Ponadto przeprowadzono własne badania pirostatyczne prochu JA-2 (produkcji Nitrochemie AG) oznaczonego jako LO5460. Badania te przeprowadzono w komorze manometrycznej o pojemności 200 cm³. Na podstawie zarejestrowanego (w czasie) ciśnienia gazów prochowych określono siłę prochu, kowolumen gazów prochowych oraz krzywe żywości dynamicznej. Wykorzystując wyniki pomiarów geometrii ziaren prochu określono współczynnik liniowej szybkości spalania. Wyniki badań własnych pozwoliły na przeprowadzenie wstępnych badań symulacyjnych zjawiska strzału w 120 mm układzie miotającym.

1. Introduction

The development of future ammunition with improved ballistic parameters and propellant systems is aimed at improving the energy, ballistic and performance properties of conventional single-base, double-base and multi-base propellants and developing new propellants with an eco-friendly chemical composition (so called 'green propellants') to enable:

– an increase in initial velocity, in particular in conventional propellant systems,
– a decrease in internal barrel surface wear for improved service life and weapon accuracy,
– a decrease in ammunition sensitivity to mechanical and thermal factors (during transport, storage and operation),
– an increase in stability of ballistic ammunition properties resulting from wide ranging changes in ambient temperature.

Ammunition with reduced sensitivity to mechanical and thermal factors can be classified into two groups [1]:

– IM (Insensitive Munitions): IM is ammunition containing propellants with improved resistance to mechanical factors, including projectile, fragment or hollow charge impact. The propellants used in such ammunition usually include nitrocellulose and are sensitive to increased temperature (*e.g.* as a result of heating).
– LOVA (Low-Vulnerability Ammunition): A reduced sensitivity of propellants for this ammunition (also referred to as LOVA propellants) is often related to a higher priming pulse threshold and reduced combustion rate at lower propellant gas pressures.

Table 1. First generation LOVA propellant composition

Component	Propellant content [%]	
	XM-39	M-43
Nitrocellulose, NC (%N)	4.0 (12.6)	4.0 (12.6)
Centralite I	0.4	0.4
Potassium sulfate, K_2SO_4	1.2	–
Hexogen, RDX	74.8	76
Acetyl triethyl citrate, ATEC	7.6	–
Cellulose acetate butyrate, CAB	12.0	12
BDNPA/BDNPF	–	3.8/3.8

The concept of composite propellants was developed during the Second World War, when the first propellants containing a solid oxidiser suspended in a plasticized polymer matrix (binder) were developed. In the last 50 years, many compositions were proposed and tested, with the majority containing 70-80% high energy filler – usually hexogen (RDX) or octogen (HMX), 10-25% polymer and one or more plasticizers. Both RDX and

HMX show a positive enthalpy, good oxygen balance and high thermal resistance making them an attractive alternative in insensitive propellants to the sensitive nitroglycerine, *i.e.* LOVA, 1st generation XM-39 and M-43 propellants (Table 1).

It was decided that the preliminary compositions of LOVA propellant designed at the Faculty of Advanced Technologies and Chemistry [2] would be:

a) high-energy filler, 72% to 80%, including one of the following three components:
    – RDX or
    – RDX/nitroguanidine (NQ), or
    – NQ/NH_4ClO_4,
b) polymer, 14% to 18%, including one of the following three components:
    – cellulose acetate butyrate (CAB) or
    – CAB/nitrocellulose (NC) or
    – NC/hydroxypropyl methylcellulose (HPC),
c) plasticizer, 6% to 10%, including one of the following two components:
    – acetyl triethyl citrate (ATEC),
    – ethyl glycol dinitrate (DEGDN).

Research into the development of LOVA propellant technology in Poland required additional reference data to evaluate the ballistic properties of the newly developed propellants. Subsequently, simulation tests in which the new Polish ammunition (with LOVA propellant) will be used, should be carried out using the actual data on propellant grain shape and energy-ballistic properties including: propellant force, co-volume, dynamic vivacity and combustion rate. The characteristic values can be obtained from closed-vessel tests.

At the initial stage of the research and development project, JA-2 propellant (in particular the geometric properties and energy-ballistic properties of the propellant grains) was used as the standard propellant to compare with the newly developed insensitive propellant. Figure 1 shows the propellant force for the propellants developed through the years [3]. The values of JA-2 propellant force lie between those reported for LOVA propellants: XM-39 and M-43.

The article includes an analysis of the available literature on energy and ballistic properties of LOVA and JA-2 propellants. Closed-vessel tests of JA-2 propellant (manufactured by Nitrochemie AG, designation LO5460) were carried out. The tests were carried out in a 200 cm^3 closed vessel.
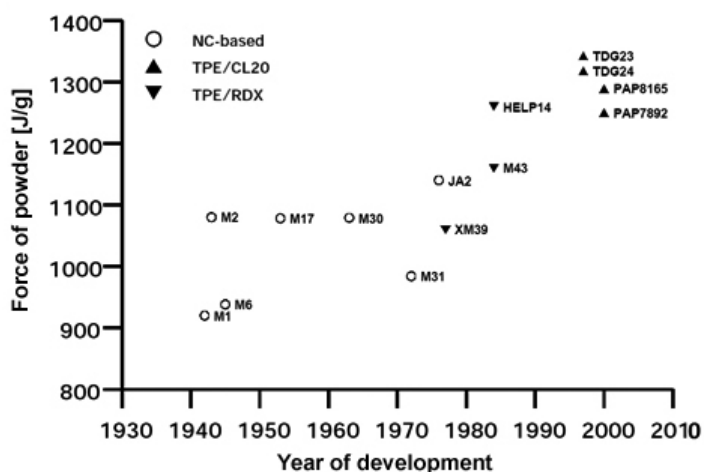

Figure 1. Comparison of JA-2, XM-39 and M-43 propellant forces with the selected propellants developed between 1930 and 2010 [3]

From the propellant gas pressure/time records, propellant force, propellant gas co-volume and dynamic vivacity curves were determined. Using the propellant grain geometry dimensions, a linear coefficient of the combustion rate was determined. The authors' own research data enabled the carrying out of the preliminary simulation tests of the 120 mm propellant system.

2. Literature analysis and JA-2 propellant tests

The JA-2 propellant used in the 120 mm M829A1/A2 tank ammunition APFSDS-T rounds is classed as a double-base propellant (Fig. 2), manufactured using Surface Coated Double Base (SCDB) technology. The propellants, apart from nitrocellulose (approx. 13.2% N) and nitroglycerin (NG) often include DEGDN (Table 2). The original grain shape was cylindrical, 7-perforated and 15.5 mm long (Fig. 3).

Table 2. Components of two-base M8 [5] and JA-2 [6] propellants

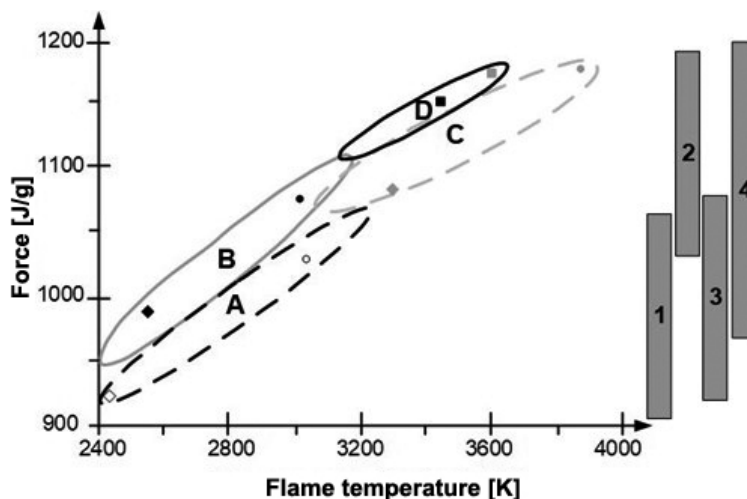| Propellant	NC	NG	DEGDN	Diphenylamine	Centralite I	Akardite II	KNO$_3$
M8	52.15	43.0	–	3.0	0.6	–	1.25
JA-2	59.5	14.9	24.8	–	–	0.7	–

Figure 2. The comparison of:
– single-base (A),
– triple-base (B), and
– double-base propellants (including: – NG (C) and – DEGN/(NG) (D))
in the propellant force – combustion temperature coordinate system allowing for the intended use of the propellant:
– for small and medium-calibre projectiles (1);
– mortar (2);
– artillery (3);
– tank (4)),
and selected brands: – JA-2 (■); – L1 (■); – M1 (◊); – M5 (♦); – M9 (●); – M10 (○); – M15 (♦); – M30 (●) [4]
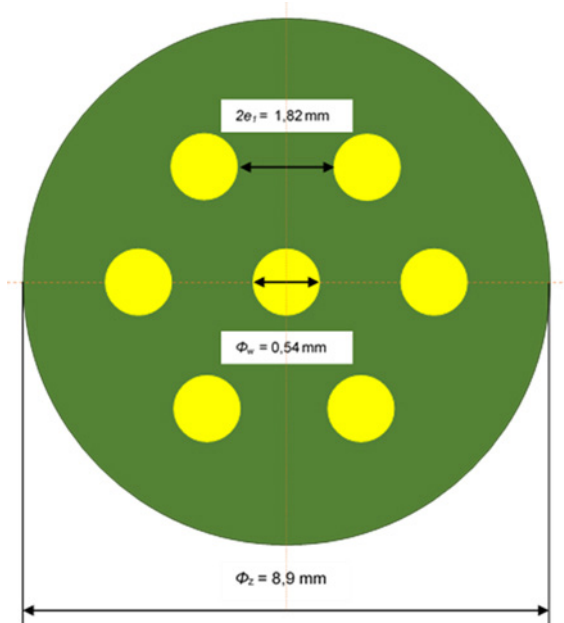
Figure 3. Characteristic JA-2 propellant grain dimensions in its cross-section

The basic energy and ballistic properties of the propellants were determined using measured pressure $p(t)$ and maximum pressure (p_{m}) of the high temperature propellant gases in a closed vessel, with a specific volume (W_0) during combustion of different mass (ω) – and different loading densities ($\Delta = \omega/W_0$) – of propellant charges. Representative closed-vessel test results for the original JA-2 propellant (carried out in a 700 cm³ closed vessel in accordance with STANAG 4115 [7] and published in [6]) are shown below. Figures 4 and 5 show the dynamic vivacity (as a function of p/p_{max}) and the combustion rate (as a function of p). The values of power coefficient (β) of the combustion rate power law ($r = \beta \cdot p^{\alpha}$) are expressed in [m/s·(MPa)$^{\alpha}$]. The dynamic vivacity was determined using the following relationship

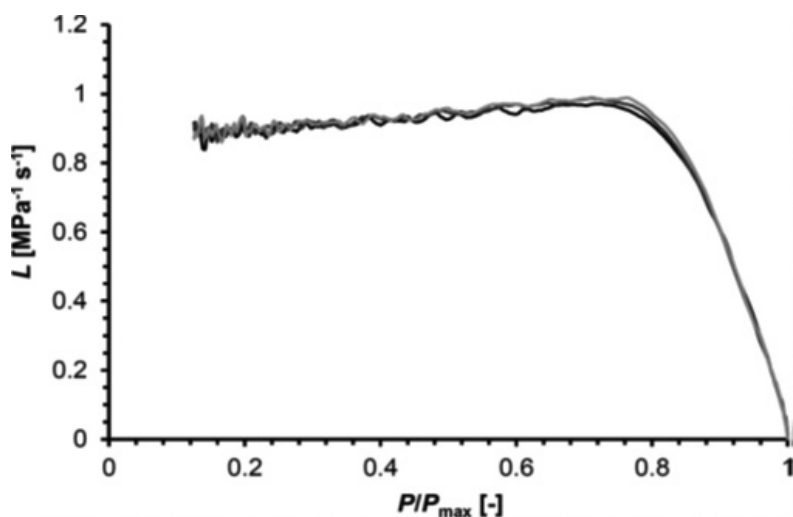$$L\left(\frac{p}{p_{max}}\right) = \frac{\dfrac{dp}{dt}}{p \, p_{max}} \qquad (1)$$

Figure 4. Dynamic vivacity (experimental) of the original JA-2 propellant [6]

$r = 0.00199P^{0.84740}$

$r = 0.00191P^{0.85838}$
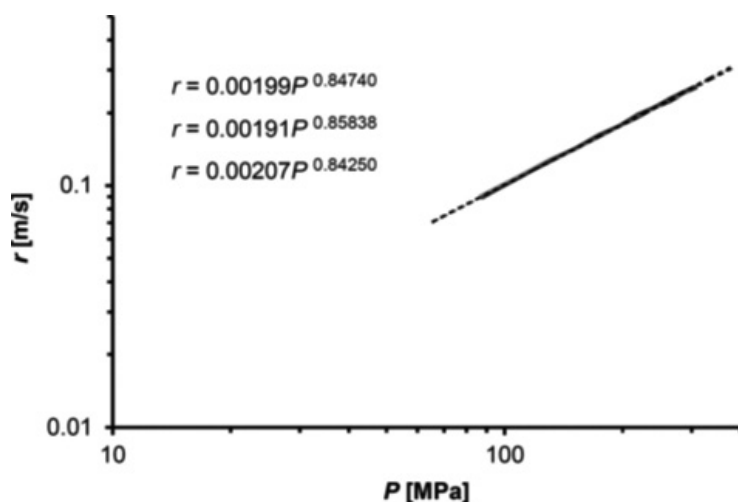
$r = 0.00207P^{0.84250}$

Figure 5. Combustion rate of the original JA-2 propellant [6]

The authors' own testing of JA-2 propellant (LO5460) was carried out in the Ballistics Laboratory of the Institute of Armament Technology at the Faculty of Mechatronics, Armament and Aerospace of the Military University of Technology, at the test stand which included the following components:

- closed vessel, a thick-walled, cylindrical $W_0 = 200$ cm³ vessel for propellant combustion in isochoric conditions (Figs. 6 and 7),
- 5QP 6000M piezoelectric pressure transducer converting the mechanical value (pressure) into a corresponding electric charge,
- TA-3/D Vibro-Meter charge amplifier sending a voltage signal proportional to the measured pressure to the processing device,
- 12-bit, 4-channel DAS-50 Keithley (USA) analogue-digital converter converting an analogue signal from the charge amplifier to a digital signal,
- data recorder (PC) storing and processing the measurement results.

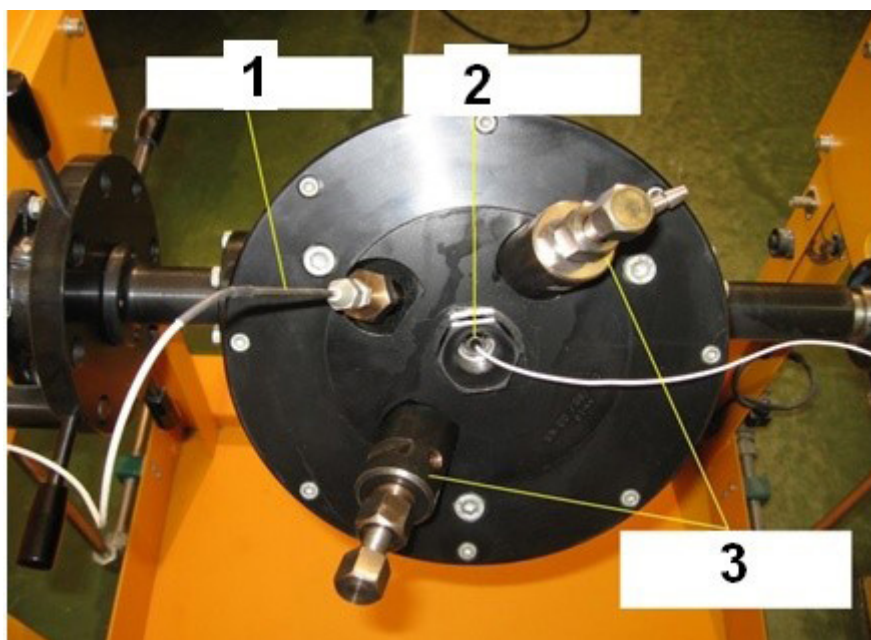**Figure 6.** AVL-HPI (Austria) closed vessel on a transport trolley

Figure 7. Closed vessel – view from the bottom with the measuring instrument seats: 1 – temperature transducer PT-100, 2 – pressure gauge 5QP 6000M, 3 – gas relieve valves

Propellant combustion was initiated using kb-2 black powder generating a 3 MPa ignition pressure. Two tests for the loading densities of 100 and 200 kg/m³ were carried out. Based on the propellant gas pressure/time recorded in the closed vessel, the propellant force and co-volume were determined and the effects of heat losses on those parameters, determined. In the next step, the exponent of the combustion rate law and the dynamic vivacity curves were determined.

To determine the energy parameters of the propellant, the Noble-Abel equation of state (NA):

$$pv = \frac{nRT}{1 - \frac{\alpha_p}{v}} \tag{2}$$

and the virial equation of state (*W*):

$$pv = nRT \left(1 + \frac{\beta}{v} \right) \tag{3}$$

were used. The symbols used in the equations: p – pressure, v – specific volume, n – number of moles, R – universal gas constant, T – temperature, α_p – co-volume, β – virial coefficient.

Table 3 includes energy parameters for JA-2 (LO5460) propellant determined based on the authors' own testing. The correction allows for the heat losses. NA refers to the Noble-Abel equation of state, whereas *W* refers to the virial equation of state.

Table 3. Energy parameters for JA-2 propellant

Parameter	Unit	LO5460	
		without correction	with correction
Propellant force:			
– *NA*	MJ/kg	1.020	1.169
– *W*		0.981	1.135
Co-volume	dm³/kg	1.359	1.019
Virial coefficient		2.245	1.468

The corrected LO5460 propellant force was compared with the data in [6]. The study specified a value of 1.153 MJ/kg for JA-2 propellant and 1.165 MJ/kg for a JA-2 equivalent without plasticizer, and 1.120 MJ/kg for propellant with 4% plasticizer content. The propellant gas co-volume specified in [6] was 0.98 dm³/kg. The values are close to the estimates allowing for heat losses correction. The values were determined based on the tests carried out in a 700 cm³ closed vessel, at lower thermal loss conditions. Based on the combustion rate law:

$$\frac{d\psi}{dt} = \Gamma(\psi) \, p_0 \left(\frac{p}{p_0} \right)^{\alpha} \tag{4}$$

where: t – time, ψ – relative burnt mass (volume) of the propellant, p_0 – ambient pressure, Γ – dynamic vivacity, α – exponent in the burning law. To determine the α exponent value, the method proposed in [8] was used.
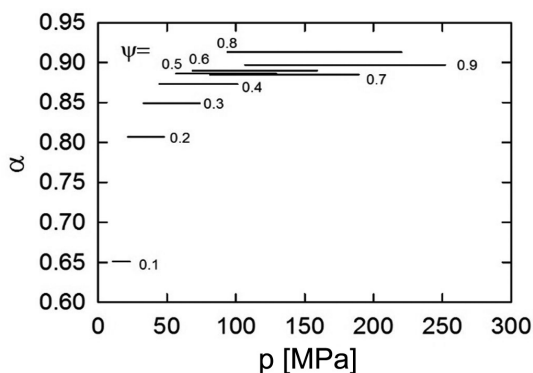
Figure 8. The calculation results for the combustion rate law exponent for - LO5460 propellant

For JA-2 type LO5460 propellant with a ψ value range of 0.1 to 0.4, the effect of initial overheating of the propellant grains can be observed, resulting in a lowering of the combustion rate law exponent values. Similar α values were obtained for $\psi \in [0.5; 0.9]$. An average α for the range ψ is 0.894 (Fig. 8). Using the combustion rate law exponent, the dynamic vivacity curves can be determined.

Figure 9 shows the dynamic vivacity curves, defined by Equation 1 for LO5460 propellant obtained from the authors' own results [9]. $L(p/p_{max})$ curves for different loading densities do not correspond to each other. They also differ from a $L(p/p_{max})$ curve – an average for the curves shown in Figure 4 (dotted line). The curves $L(p/p_{max})$ determined based on authors' own research suggest that the tested propellant shows more progressive characteristics than the propellant analysed in [6]. This may be due to different geometric dimensions of the propellant grain or the effects of heat losses. The curve in study [6] was obtained based on the results of tests in a 700 cm³ closed vessel, whereas a 200 cm³ closed vessel was used in the author's own research. The heat losses are lower in the larger vessel – so p, p_{max} and dp/dt will be higher. Since p and dp/dt increments compensate each other, the p_{max} increment is a decisive factor. The ratio of maximum pressure allowing for and not allowing for the heat losses, shows that for a loading density of 100 kg/m³ it is 1.1, and for a loading density of 200 kg/m³ it is 1.048. The curves shown in Figure 10 can be plotted by dividing the calculated L values by those values. They are similar in shape to the curve shown in Figure 4.
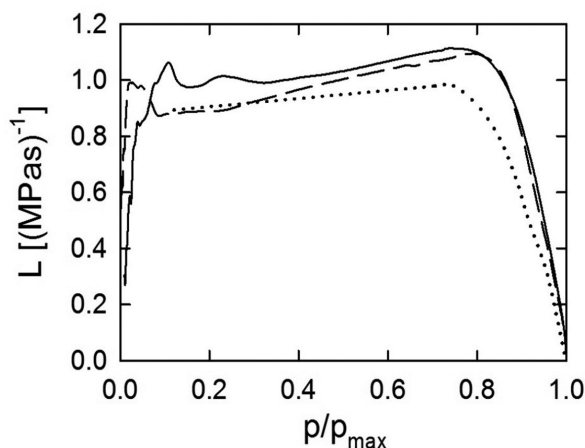

Figure 9. The dynamic vivacity curves for LO5460 propellant determined using the Equation 1; solid line $\Delta = 100$ kg/m³, broken line $\Delta = 200$ kg/m³, dotted line – averages from Figure 4
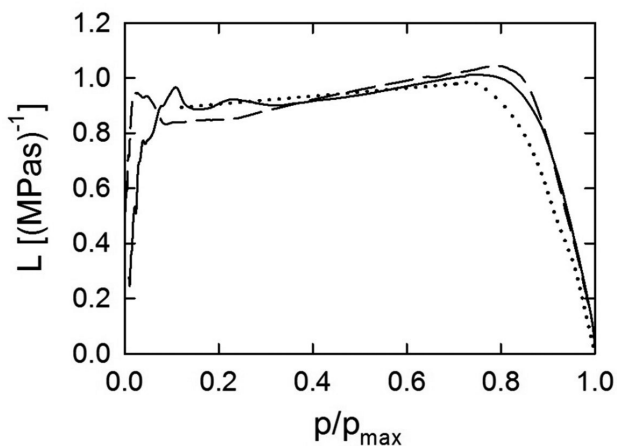
Figure 10. The dynamic vivacity curves for LO5460 propellant determined using the Equation 1 and calculated allowing for the heat losses; solid line $\Delta = 100$ kg/m³, broken line $\Delta = 200$ kg/m³, dotted line – averages from Figure 4
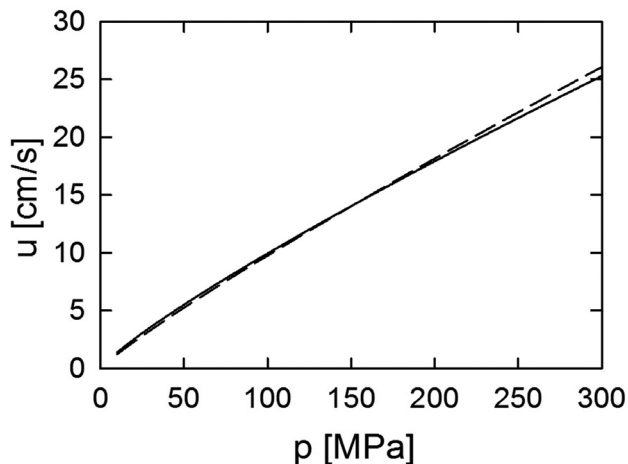

Figure 11. Relationship between JA-2 propellant combustion rate and pressure: broken line – average values calculated from Equations 5, solid line – author's own research

In [6], the relationship between the combustion rate and pressure was approximated using the following three relationships:

$$u = 0.199p^{0.8474}; \quad u = 0.191p^{0.85838}; \quad u = 0.207p^{0.8425}, \quad [u] = \text{cm/s}, [p] = \text{MPa} \tag{5}$$

The mean exponent (0.85) is slightly lower than that determined in the authors' work (0.894).

Figure 11 shows the linear average combustion rates for the values determined using Equations 5 and determined in the authors' own research. A good agreement of the combustion rates can be observed. At higher pressures, a relatively low non-conformity of the linear combustion rate value can be observed. This results from the higher combustion rate law exponent determined in the authors' own research. The evaluation of JA-2 propellant combustion rates shows results corresponding to the literature data.

3. Preliminary shot simulations

To simulate a 120 mm tank gun shot, a physical model of the propellant system was developed and a mathematical model of the phenomena occurring during the shot was formulated based on STANAG 4367 [10] requirements, allowing the Thermodynamic Interior Ballistic Model to be solved. To solve the system of equations of the mathematical model and carry out the numerical simulations, computer software was developed. The simulations were developed for an armour-piercing, fin stabilised, discarding sabot, practice shell with tracer (APFSDS-T-TP). The single-component propellant charge in the analysed system is based on JA-2 propellant with cylindrical 7-perforated grains – LO5460. Tables 4 and 5 show the data used in the calculations. The recoil system parameters were taken from [11].

Table 4.   Weapon (smoothbore) and APFSDS-T-TP round specifications

Parameter	Unit	Value
Mass of recoil parts, M_{zo}	kg	3300
Bore, d	mm	120
Bore length, l_w	m	4.7
Volume of empty cannon chamber, W_0	dm^3	9.8
Projectile weight, m	kg	4.8
Recoil system constant, k_s	N/m	1450
Initial recoil resistance force, F_0	N	12000

Table 5.   Single-base propellant charge (7-perforated LO5460 propellant) specifications

Parameter	Unit	Value
Number of propellant charge components, n	−	1
Propellant mass, ω	kg	7.25
Propellant force, f	J/g	1020[a]
Flame temperature, T_1	K	3450
Combustion rate law exponent, N	−	0.894[a]
Combustion rate law coefficient, A	m/(s·Pa^N)	0.07·10^{-7}[a]
Ratio of specific heats	k	1.2
Propellant gas co-volume, α	dm^3/kg	1.359[a]
Propellant density, δ	kg/m^3	1600
Propellant grain length, L	mm	15.5[a]
Propellant grain diameter, D		8.78[a]
Perforation diameter, P		0.546[a]
Combustible layer thickness, e_1		0.893[a]

[a] *author's own research*

Figures 12 and 13 show the plots of general shot parameters from the simulation calculations using the developed software, geometric dimension data of the LO5460 propellant grains and the energy and ballistic properties from the authors' own work.
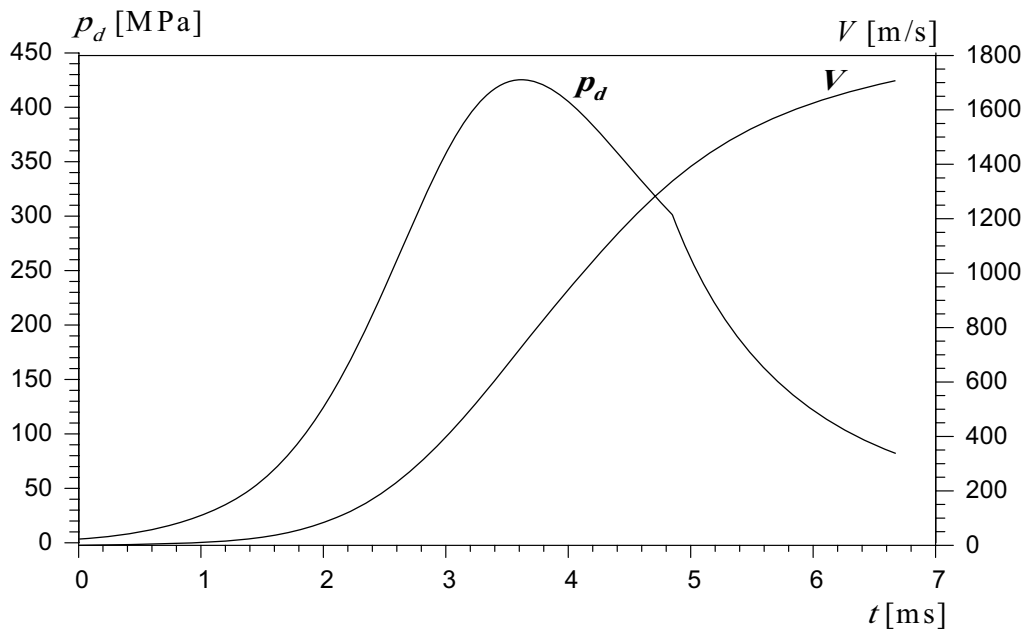
Figure 12. Breech pressure p_d and projectile velocity V as a function of time t
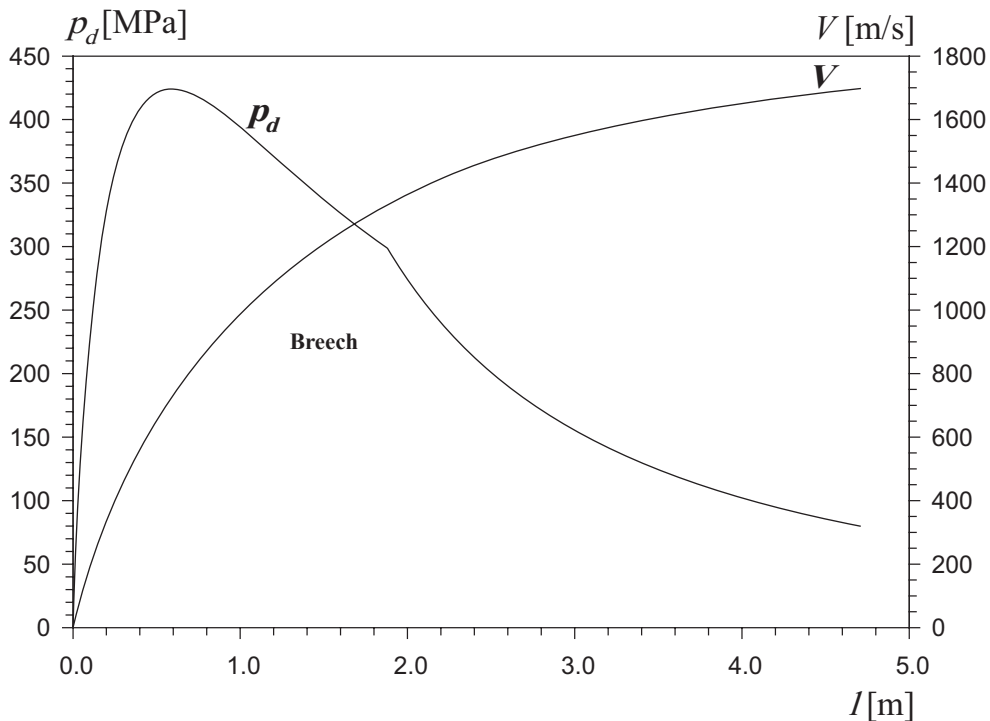

Figure 13. Breech pressure p_d and projectile velocity V as a function of length l

In accordance with [12, 13], the actual discharge parameters for 120 mm target practice round APFSDS-T-TP are presented as follows:

– maximum propellant gas pressure: 430 MPa,
– projectile muzzle velocity: 1715 ±20 m/s.

The simulated test results obtained at this stage, indicate a correctly developed mathematical model of the gun shot and input data (obtained in the authors' research on JA-2 propellant). The developed computer software enables an analysis of the ballistic curves for multiple charges (allowing for the combustible charge case) other than with 7-perforated grains.

4. Conclusions

1) The authors own closed-vessel tests of JA-2 propellant with LO5460 type propellant grains show that:
   a) the determined values of energy parameters correspond to literature data. After correcting the values for heat losses, propellant force values typical for LOVA propellants are obtained,
   b) an analysis of the dynamic vivacity of the propellants confirmed the validity of the physical combustion rate law. The dynamic vivacity curves at different loading densities correspond to each other, apart from the initial and the end sections,
   c) a comparison of the LO5460 propellant combustion rate curves and literature data for JA-2 propellant, shows good agreement.

2) The following conclusions can be drawn from the preliminary calculated results for the 120 mm APFSDS-T-TP round:
   a) a satisfactory agreement between actual and calculated shot parameters, *e.g.* maximum gas pressure in the barrel and muzzle velocity, can be achieved,
   b) since the calculations were carried out at normal temperature, the following correction factors were used: burning rate temperature factor $f_{\beta T} = 1$ and propellant force temperature factor $f_{fT} = 1$.

Acknowledgements

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