THEORETICAL AND EXPERIMENTAL DETERMINATION OF INTERIOR BALLISTIC PARAMETERS OF RECOILLESS GUN

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This paper addresses a method for the determination of the interior ballistic main parameters applied for a recoilless armament system with thermobaric ammunition based on several physical assumptions regarding the gun propellant system, mechanical behavior of the barrel, combustion and heat transfer properties. In general, the internal ballistics is based on both thermodynamic aspects and fluid dynamics of the two phases that predict the evolution of the pressure in the combustion chamber and the muzzle velocities of the projectile fired. Ballistic parameters were obtained by numerical processing and were compared with the experimental data in order to analyze the converge of the two sets of data in an attempt to demonstrate the accuracy of the method. Some issues that were met in performing such calculations were analyzed and correlated to experimental observations. The agreements between them are satisfactory.

Keywords: internal ballistics, recoilless rifle, reactive projectile

1. Introduction

Among armament systems employed in modern military capabilities, recoilless rifles are used for their superior performances regarding muzzle velocity, firing accuracy, variety of projectiles fired and maneuverability. Due to their peculiarities, the propellant combustion products are ejected from the chamber through the nozzle (de Laval) and thus creating a thrust force for the projectile in the opposite direction.

In many works, a geometric law of burning (at any given fraction of burnt propellant, the remaining grains are formed only by removing parallel layers from the initial shape, without accounting for phenomena such as grain fracturing, erosion or anisotropic burning), first proposed by the French researchers Vielle

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and Saint Robert and later extended for recoilless guns by Serebryakov, is used for describing various propellants performances [1, 2]. Other papers propose a unified mathematical model based on a modified two-dimensional fluid flow in order to describe the non-equilibrium two-phase flow characteristics in both barrel and nozzle [3] using Arbitrary Lagrangian-Eulerian (ALE) approach. Similar numerical approaches have been studied using algorithms based on Résal's energy balance model enlarged to cover spherical and perforated propellants [2]. A more adaptative method, in which an adiabatic transformation is based on a mathematical model, was centered on the energy balance of the unburned products and gases [4]. Recently, a more complex model has been presented by Elsadek et al. [5] for which, Interior Ballistic Lumped Parameter Model (IBLPM), with single propellant and mixed propellant, and one-dimensional two-phase flow model (1D-TPFM) were carried out. The governing equations of the mass, momentum and energy for both phases over a control volume of gas and solid phases are solved using an Euler approach. Nevertheless, an isothermal model, similar to the one used in this paper, was presented by Kapur [6] and Nusca [7], based on three simplifying assumptions: (a) kinetic energy is neglected, (b) the covolume is neglected and (c) zero shot-start pressure is assumed.

The objective of this paper is to present a suitable ballistic model of an armor piercing thermobaric ammunition (Fig. 1) designed to be fired from a recoilless rifle. This ammunition is intended to combine thermobaric and perforation effects, being thus lethal to personnel in enclosed spaces as well as in open field, through the intermediary of propelled fragments.

a.

b.

Fig. 1. A 3D CAD model of the projectile (a) and the experimental model before firing (b)

The ammunition is designed to be fired from the 73 mm caliber anti-tank grenade launcher "Spear" SPG-9 recoilless rifle, in order to enlarge the range of ammunitions that can be fired from this system. The new projectile uses the same propellant charge and rocket engine as the classical high-explosive anti-tank grenade PG-9 shaped charge ammunition. The projectile is made out of high-grade structural steel, and uses a thermobaric explosive dispersed by an inner concentric sheath filled with composition B (a mixture of trinitrotoluene and cyclotrimethylenetrinitramine). Due to its piercing nature, it is initiated by means of a delay base fuze.

The internal ballistics were calculated by means of numerical integration, using MathCAD software, and experimental data was obtained by real firings, where pressures and muzzle velocities were measured.

2. The internal ballistics

The mass of the projectile was 3700 ±75 g. The variations arose from the manufacturing process, and were due to the forging process and the fact that no machining is performed on the inside of the projectile after this step. The mass that is considered in the following equations is 5500 g, due to the supplementary 1800 g mass of the rocket engine.

2.1. The internal ballistics of a recoilless rifle

The internal ballistics studies the physical and chemical phenomena that take place from the ignition of the primer until the moment the projectile leaves the bore. Its main purpose is to determine the processes that take place and to determine the velocity of the projectile, the maximum pressure inside the burning chamber and the accelerations that are enforced on the projectile [8].

In order to describe the physical process and to create a mathematical model, to establish a set of equations, some initial assumptions are required [1, 11]:

- the burning law of the propellant is linear and proportional to the pressure;
- a covolume of the gasses will be considered, and it is temperature-independent;
- the barrel deformations are negligible;
- there are no losses in the form of unburned propellant through the nozzle. However, this will be considered later by means of a coefficient;
- the transition from a constant volume burning to the period in which the nozzle flow is present is instantaneous and the flow can be approximated as quasi-stationary.

In contrast to the models that describe the classic ballistics of a gun, the recoilless rifles can be analyzed with the model of the leaking gun internal ballistics [9, 10] (Fig. 2). The applications of such a model encompass a large category of firearms, ranging from recoilless rifles to mortars, and at the same time it can be used to describe the worn bores, highlighting the variations of the performance characteristics that can appear in the use of a firearm.

When designing a new projectile for an existing system, it is necessary to consider for certain elements, such as the bore's strength and the wearing level that the new projectile is causing to the bore. The main factors that influence these effects are the kinetic energy of the projectile, the momentum and the maximum value of the pressure.

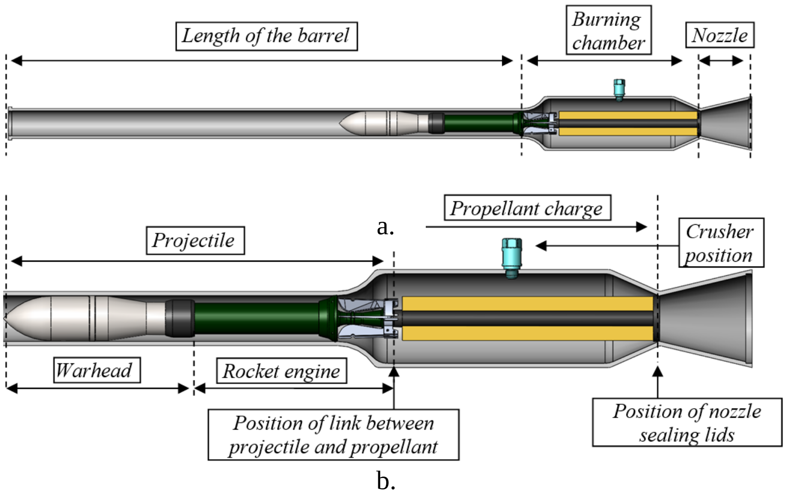


Fig. 2. Representation of the projectile and the propellant charge inside the barrel, before firing (a), and a detailed view (b).

Due to the nature of the gun and taking into consideration the pressure variation during the entire period specific to the internal ballistic, it is observed [11] that the maximum value of the pressure is achieved at relatively small values of the projectile displacement (under 10% of the total length of the barrel). This, in correlation with the much bigger volume of the burning chamber than that of a classic gun and therefore an increased fictive length (the fictive length of the barrel is a parameter usually used to appreciate the dimensions of the burning chamber in respect to the caliber of the firearm and is defined by the volume of the chamber divided by the bore diameter) of the burning chamber is an indicative of the small influence that the increase in the mass of the projectile has on the maximum value of the pressure. Hence, by keeping the same mass of propellant as for lighter projectiles will not result in a critical increase of the pressure.

The propellant is comprised of double-base lamellar grains (the propellant individual elements have two dimensions much larger than the third one, in order to maximize the burning surface), with a burning thickness of 0.62 mm (NBL-62). The mass of the propellant charge is 785±5 g. The ignition is performed by means of a primer filled with black powder and two electric igniters. These two igniters are set off by two electrical contacts placed in the critical section of the nozzle.

In order to proceed with the mathematical model, the burning of the propellant charge is divided into two main periods, preceded by a preliminary phase. The preliminary burning, which starts from the initiation of the electric primers, covers the burning of the black powder and an initial phase where the main propellant charge burns until the pressure obtained in the chamber reaches a value necessary to break the two lids that cover the nozzle, and the link that keeps the projectile and the propellant charge together. These are considered to happen simultaneously, and usually the elements (the lids and link) are dimensioned to ensure that their break occurs at pressure values as close as possible to each other.

The pressure resulted from the black powder is the starting pressure for the burning of the double-base propellant. In order to determine this pressure, the global reaction was necessary to be written. Although the chemical formula of the charcoal used in black powders varies, an empirical approximation can be written as C_7H_4O. With this assumption, the reaction becomes:

$$6KNO_3+C_7H_4O+2S \longrightarrow K_2CO_3+K_2SO_4+K_2S+4CO_2+2CO+2H_2O+3N_2$$

Out of all the products, there were further considered the gaseous ones (CO_2, CO, H_2O, N_2). The volume in which these gasses will expand is the loading chamber volume from which the propellant volume is subtracted. This is considered to be a constant volume burning, and the initial temperature of the gasses is close to 2200 K (the burning temperature of the black powder). The value of the pressure is calculated to be 6.92 MPa and considered as the starting value for the burning of the main propellant charge.

This initial phase continues with the burning of the main propellant charge. It is considered to be an isochoric process. The end of this phase is marked by the breaking of the lids that seal the nozzle. This phase is a short one in comparison to the total time of the internal ballistic, around of 0.7 ms, and only ≈0.5 % of the total mass of propellant charge is consumed [11].

- Phase 1

This phase begins together with the projectile movement. The propellant burning continues, maintaining an increase in the pressure. During this phase, the maximum value of the pressure is reached. The movement of the projectile inside the barrel increases continuously the burning volume. The pressure accelerates the projectile and also increases the burning rate. The flow of gasses through the nozzle is considered to be quasi-static and supersonic. The total fraction of gasses that are lost from the burning chamber during this period can be calculated by integrating the flow, and is equal to ≈60 % by the end of this phase [11]. The flow through the nozzle is allowed to cancel the recoil, by creating a reaction force. An effect of this flow besides the drop in pressure is the lower temperature that the gasses will have as opposed to a classic barrel. Due to these reasons, the starting mathematical model of an isochoric burn is no longer suitable, and a set of equations are appropriate to be used (equations (1) to (7)). The relative temperature is calculated, giving an average solution between isochoric and isobaric burning. The end of this phase is marked by the burning of all propellant. The maximum value of the pressure is around 68.35 MPa.

- Phase 2

This phase starts with the end of the burning and ends at the moment when the projectile leaves the barrel. No more changes in the equation set or value of coefficients appear during this phase.

The equations used to determine the internal barrel pressure, acceleration and velocity of the projectile are those presented by J. Corner in "*Theory of the interior ballistics of guns*" [1]. The most complete set of equations is when the nozzle is open, the projectile is in motion, and the propellant is not completely burnt, and by setting different variables to fixed values (before pressure is high enough to open the nozzle S = 0. Before it is high enough to start the projectile, x = 0. Before the propellant is all burned, φ is less than 1; after it is all burned φ = 1), it can be made to describe different phases:

$$P\left(U + Ax - \frac{C}{\partial}\right) = NCRT\left(1 + \frac{kCN}{6W}\right) \tag{1}$$

The equation of state for the gasses inside the barrel is

$$W_1 \frac{d^2x}{dt^2} = AP \tag{2}$$

Further, Newton's second law written for the projectile and the remaining propellant mass at any given moment is

$$W_1 = W + \frac{1}{2}kCN\,, \tag{3}$$

while the modified shot weight, taking into consideration the mass of propellant accelerated is

$$D\frac{df}{dt} = -\beta P^{\alpha} \quad . \tag{4}$$

The burning law for the propellant, pressure dependent, is described by

$$\phi = (1 - f)(1 + \theta f) \tag{5}$$

and the ratio of burnt propellant is written in respect to the web size. The iterations are made by incrementing the value *f*, therefore the ratio of burnt propellant will be slightly different, due to the form of the grain (lamellar):

$$\frac{dN}{dt} = \frac{d\phi}{dt} - \frac{\psi SP}{C(RT)^{1/2}} \quad . \tag{6}$$

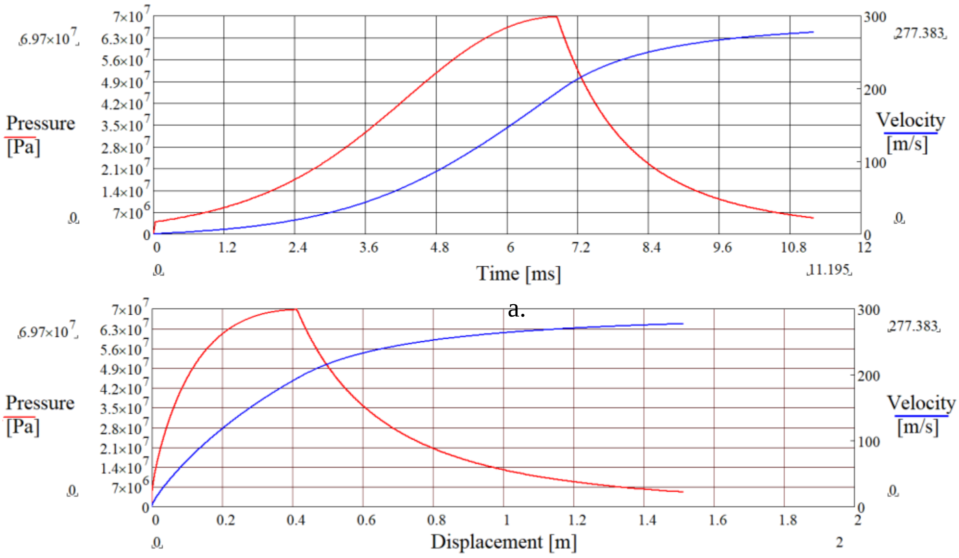
The gas flow (losses) through the nozzle is given by equation (7), as a global equation, derived from (1)-(6):

$$\frac{d(NT)}{dt} = -(\gamma - 1)\frac{AP}{CR}\frac{dx}{dt} + T_0\frac{d\phi}{dt} - \frac{\gamma\psi SP(RT)^{1/2}}{CR} \tag{7}$$

where:

- P - Chamber pressure;
- U - Chamber volume;
- A - Cross sectional area of the bore;
- C - Propellant mass;
- δ - Propellant density;
- R - Gas constant;
- N - Ratio of gasses that escaped through the nozzle;
- W - Effective shot weight;
- W_1 - Modified projectile weight (taking into consideration the mass of propellant accelerated);
- k - Numerical factor;
- T - Temperature of the gasses;
- D - Initial web size;
- β - Burning coefficient of the propellant;
- φ - Ratio of burnt propellant;
- θ - Form factor of the grain;
- S - Throat section of the nozzle;
- ψ - Quantity describing the effect of leakage;
- γ - Molar heat ratio of the gasses;
- f - Coefficient for the web size after burning;
- x - Projectile displacement;
- α - Pressure exponent (constant and specific to each propellant);

The evolution of the pressure and velocity with respect to time and displacement of the projectile inside the barrel are presented in Fig. 3.



b.

Fig. 3. Pressure and velocity plots vs time (a) and displacement of the projectile inside the barrel (b)

3. Experimental data

A series of real firings were made, both with a combat rifle, and with a crusher gun. The internal pressure was measured using copper crushers (Fig. 4 and Fig. 5). These crushers are a series of precision-made copper cylinders, that are axially pressed and pre-deformed at a known force.

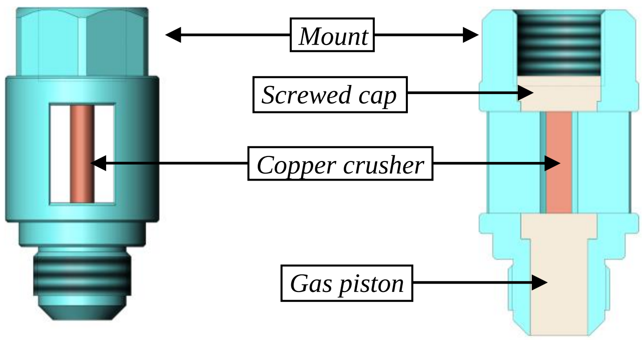


Fig. 4. The copper crusher assembly

Fig. 5. The testing launcher in firing position with the copper crusher assembled

Then, they are installed in a special port placed in the burning chamber, and through the action of a piston, the pressure inside the barrel acts on it and creates a load that further deforms the crusher. Then, the amount of deformation is translated to the level of force required, and the maximum internal pressure is determined. The pressures measured are presented in Table 1.

The velocity of the projectile was measured using a Doppler radar (Fig. 6), with a flame detector used as a trigger for the beginning of the measurement. Both real and inert rocket engine were used in the experimental ammunition.

To estimate the time that the projectile spends inside the barrel, a high-speed video camera (Photron Fastcam SA3 model 120K-C2 with a Sigma zoom lens, 24-70 mm, 1:2.8 EX DG Macro, placed 15 m away from the launcher, at a 1/5000 s shutter speed, 2000 fps acquisition rate, 1024x1204 pixels resolution) was used, and the time was approximated from the detection of flame at the nozzle. Even though this moment is actually only an approximation of the starting time of the burning, the delay between the ignition and the beginning of gas leakage through the nozzle is less than a millisecond.

Table 1

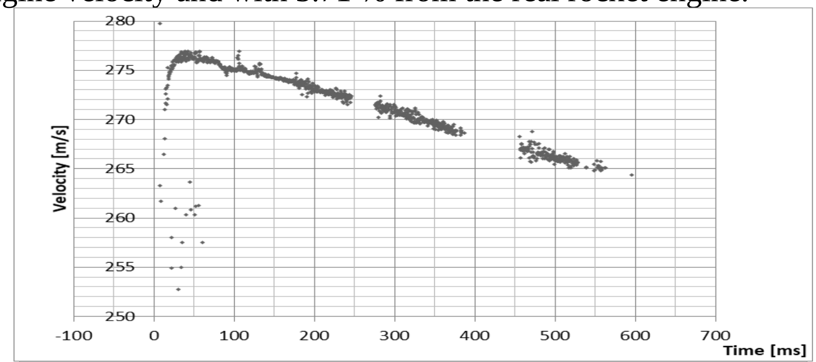
Pressures measured with the copper crushers

No.	Pressure from the first crusher [MPa]	Pressure from the second crusher [MPa]	Average value [MPa]
1.	65.41	65.66	65.53
2.	68.35	68.35	68.35
3.	74.73	73.26	73.99
4.	71.49	71.49	71.49
5.	68.65	68.65	68.65
6.	66.78	65.12	65.95
7.	65.41	66.19	65.80
8.	69.53	69.53	69.53
9.	68.65	66.98	67.81
10.	62.96	65.51	64.23
11.	69.53	69.53	69.53
Average value			68.26

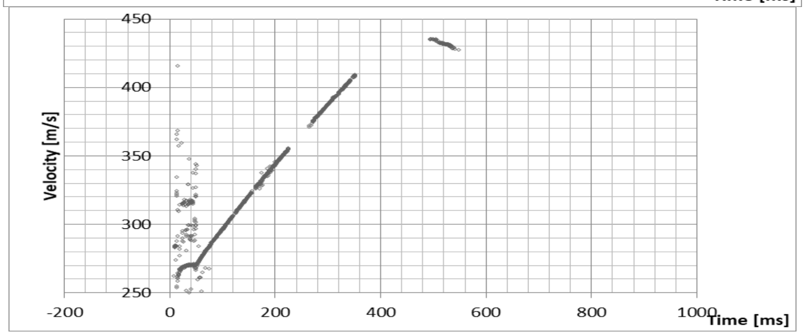
Fig. 6. The launcher in firing position with the Doppler radar placed near the barrel and a projectile ready to be loaded

The data ilustrated by the velocity-time curves (Fig. 7) correspond to the complete trajectory of the projectile between the muzzle and the target impact moment. The closest accurate and relevant velocities that can be measured may be considered from t = 27.13 ms, whereas values before this moment are without physical relevance. Until 100 ms, there can still be observed irrelevant scattered points on the graph (noise), caused by gasses and small particles expelled from the bore with the projectile.

The corresponding measured velocities for this point in time are 276.06 m/s for the inert rocket engine and 267.45 m/s for the real one. The numerical solution of the model gives a maximum velocity of 277.38 ms/s after t=10 ms. Comparatively, the calculated value varies with 1.32 % from the inert rocket engine velocity and with 3.71 % from the real rocket engine.



a.



b.

Fig. 7. Projectile velocity for inert (a) and real (b) rocket engine measured with Doppler radar

The average value for the measured pressures indicated in Table 1 is 68.31 MPa. The calculated numerical value is 69.7 MPa. Thus, the theoretical pressure is with 2.1% higher than the experimental measured values.

4. Conclusions

To obtain the interior ballistics parameters such as chamber pressure and projectile velocity, a two-phase transient method based on several simplifying assumptions has been used. Experimental measurements have been conducted using copper crushers for pressure determination and Doppler radar for the muzzle velocity. The comparative analysis indicates that the experimental values obtained differ from the calculated ones by margins of a few precent. Based on the numerical and experimental data, the internal ballistic model used in this paper provides an accurate method to describe and understand the physical phenomenon of the interior ballistic process in a recoilless armament system.

R E F E R E N C E S

[1] *J. Corner*, Theory of Interior Ballistics of Guns, New York – London, 1950;

[2] *M. Akçay*, Internal and transitional ballistic solution for spherical and perforated propellants and verification with experimental results, Journal of Thermal Science and Technology, **37, 1**, p. 35-44, 2017;

[3] *C. Cheng, C. Wang, X. Zhang,* A prediction method for the performance of a low-recoil gun with front nozzel, Defence Technology, **15 (5)**, p. 703-712, 2019;

[4] *Z. Surma,* Recoilless Gun System as a Particular Form of General Interior Ballistics Model of Gun Propellant System, Problems of Mechatronics. Armament, Aviation, Safety Engineering 2018, **9 (4),** 33-48, 2018;

[5] *H. Elsadek, X-B Zhang, M. Rashad,* Interior ballistic study with different tools, International Journal of Heat and Technology, **32 (1),** 2014;

[6] *J. N. Kapur*, The internal ballistics of a recoil-less high-low pressure gun, Applied Scientific Research, ***A 6***, p. 445–466, 1957;

[7] *J. M. Nusca*, Numerical Modeling of the Modular Artillery Charge System Using the NGEN Multiphase CFD Code Effects of Case Combustion, Proceedings of the 37th JANNAF Combustion Subcommittee Meeting, CPIA Publication **701 (2)**, pp 87–101, 2000;

[8] *A.J. Kotlar,* The Thermodynamics of Interior Ballistics and Propellant Performance, Report, Aberdeen Army Research Laboratory, 2013;

[9] *A. Rotariu, L. Matache, F. Bucur, M. Cirmaci-Matei, M. Mărmureanu, E. Trană*, Implementation of a Gumbel distribution function in interior ballistic calculations for deterred propellants, U.P.B. Sci. Bull., Series B, **82 (1)**, 2020;

[10] *J. E. Mosier*, A computer simulation of the internal ballistics of recoilless-rifle rocket launchers, University OF Missouri - ROLLA, 1970;

[11] *M. E. Serebriacov*, Internal ballistics of tube artillery systems and powder rocket / Balistica interioară a sistemelor cu ţeavă şi a rachetelor, Editura Academiei Tehnice Militare, Bucharest, 1970 (translated from Russian).