STUDY ON METHOD TO DETERMINE THE LIFE OF TESTING GUN THAT FIRES 7.62x25mm AMMUNITION

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Abstract:
The article presents a method to determine the life of a testing gun that fires 7.62x25mm ammunition. The scientific basis for determining the life of the test barrel is based on the wear of the rifling lands corresponding to the number of shots. The wear of the barrel is determined by the thermal and mechanical effects of the bullet's driving band on the lands and the grooves. The results show that: With the number of fires being 1000, 2000, 3000, 4000, 5000, and 6000 respectively, the barrel wear is 0.334mm, 0.668mm, 1.002mm, 1.337mm, 1.671mm, 2.005mm, and the muzzle velocity is reduced respectively by 1.15%, 2.06%, 2.98%, 3.67%, 4.36%, 5.28%. The accuracy of the 7.62x25mm ammunition test results is reduced due to this change. In addition, to ensure the accuracy of the measurements, the barrel needs to be replaced when the number of shots is more than 5000 shots. The paper is an important theoretical basis for determining the gun life used to test infantry ammunition.

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1. INTRODUCTION

The testing gun is a device with high accuracy specifications, used to measure the characteristic parameters of weapons during and after design and manufacture, ensuring the level of accuracy and safety for people and associated measuring equipment. Many suppliers manufacture test barrels for world-class infantry guns. Prototypea company in Brno, Czech Republic is a world-famous manufacturer of experimental gun barrels. The caliber 5.56x45mm, 7.62x51mm, and other calibers are all produced by this company, Fig. 1. In addition, these experimental barrels are distributed by many other companies such as Lothar Walther company located in the UK and Germany, Sydor Technologies company based in the US, etc. The common feature of the companies that manufacture and distribute test barrels is that they only disseminate the specifications and features of the products that are of interest to users while the theoretical basis of calculating the type design of this gun is not published. Therefore, applied the technology of designing and manufacturing this type of gun is very difficult.

Fig. 1. Some experimental barrel styles

The process of testing ammunition after manufacturing will inevitably face difficulties in ensuring the working characteristics of the test gun, especially in ensuring the long service life of the barrel. It is clear that the types of tested ammunition are ammunitions that humans have not applied all the technical characteristics such as combustion chamber pressure, belt cutting force,

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warhead hardness, etc. Therefore, these quantities can increase or decrease abnormally, directly affecting the life of the test gun. The muzzle bullet velocity is one of the important factors in evaluating the life of the barrel. Each barrel is made from perfectly fine materials, which have the required durability reserve and satisfy all structural and technical requirements. The barrel is gradually worn out after firing, leading to the muzzle bullet velocity being reduced to a certain value, at which point the test barrel will stop satisfying the initial allowable technical requirements.

The study of the wear of guns and artillery barrels has been studied by many authors. However, barrel wear is mainly calculated using the finite element method [1] or the experimental method [2-10], and there have not been any in-depth studies on the cause and origin affecting it. In this paper, the author focuses on studying the method of determining barrel wear; and then combining the law of barrel wear with the system of interior ballistic equations to establish the complete interior ballistic. The muzzle velocity is obtained when solving the complete interior ballistic equations system. Besides, the paper used the obtained result to evaluate the barrel's life.

2. MATERIALS AND METHODS

The content of the paper focused on establishing the equation to determine the barrel wear according to the number of shots. This equation is solved simultaneously with the system of interior ballistic equations to determine the parameters for evaluating the barrel life. Numerical methods are used to solve this system of equations. The calculation program is programmed on MATLAB software. The decrease in muzzle velocity with the number of shots is used to evaluate barrel life. This result is compared with the published data of the manufacturer to verify the reliability of the calculated model. The calculation is carried out on a testing gun that fires 7.62x25mm ammunition.

3. ESTABLISH THE SYSTEM OF INTERIOR BALLISTIC EQUATIONS

3.1 Determination of the temperature range of the barrel

Some assumptions used to establish the equation for determining the heat field of the barrel are as follows:

- Consider only the linear heat transfer;
- At any cross-section of the barrel, the temperature, pressure, velocity, and density of the gas flow are assumed to be uniformly distributed;
- The barrel material is considered to be homogeneous and isotropic.

We can assume that the parts are cylindrical tubes, from the general shape of the barrel. The system of differential equations for heat conduction through the barrel wall is the system of differential equations for the heat conduction of a cylinder tube [11-13].

$$\frac{\partial T}{\partial \tau} = a\left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r}\right). \tag{1}$$

The first condition: $T[0] = T_0$; $r[0]=r_1$;

The boundary conditions:

- At the inner surface:

$$\alpha_{kh}(T_0 - T) = -\lambda\left(\frac{\partial t}{\partial n}\right). \tag{2}$$

- At the outer surface:

$$\alpha_{kh}(T - t_n) = -\lambda\left(\frac{\partial t}{\partial n}\right). \tag{3}$$

Where: $a = \lambda / c\rho$; λ - the thermal conductivity of the barrel material; T - the temperature of the combustible gas; λ_{kh} - the coefficient of thermal conductivity of the combustible gas; d – caliber; α_{kh} - the coefficient of heat transfer from the combustible gas to the barrel wall:

$$\alpha_{kh} = Nu\frac{\lambda_{kh}}{d}. \tag{4}$$

3.2 Determination of barrel wear

To determine barrel wear, several assumptions are used:

- The coefficient of friction between the bullet belt and the barrel is constant when there is barrel wear;
- The assumptions when solving the interior ballistic equations are used [11], [14-19].

Barrel wear is a very complex phenomenon, and is caused by many factors. The complexity of barrel wear stems from the characteristic of the very extreme working environment in each shot. These characteristics include pressure, temperature, friction between the combustible gas and the barrel lands, etc. These are also the main causes of barrel wear. So, the level of barrel wear is determined by the amount of gas energy used to destroy the surface layer of the barrel, see Fig. 2.

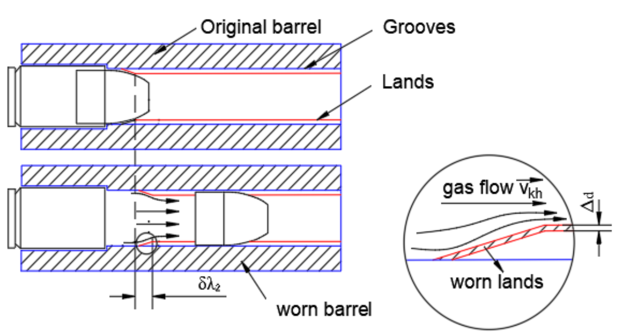

Fig. 2. The model is used to determine the barrel wear

The energy of the gas flow lost to destroy the barrel metal is determined by Darcy's formula [3]:

$$\Delta p = \xi \frac{l}{d} \frac{\gamma_{kh} v_{kh}^2}{2g}. \tag{5}$$

Where: ξ - the drag coefficient of pipes with roughness (the barrel can be considered as a rough pipe due to the spiral grooves with a depth of t_{rx}).

$$\xi = \frac{1}{(1{,}74 + 2\,lg(d/2t_{rx}))^2}. \tag{6}$$

The velocity of the gas flow:

$$v_{kh} = v \frac{l_H}{l_{bd} + l}. \tag{7}$$

In this formula: γ_{kh} is the specific gravity of the burning gas; l_H is the distance from the bottom of the combustion chamber to the top of the rifle; l_{bd} is the length of the combustion chamber.

The differential equation for energy over time t:

$$dE = S \Delta p v_{kh} dt = S\xi \frac{l}{d} \frac{\gamma_{kh} v_{kh}^3}{2g} dt. \tag{8}$$

The differential equation for energy per unit surface:

$$dE_r = \frac{\partial E}{\pi d l} = \frac{\xi}{8g} \gamma_{kh} v_{kh}^3 dt. \tag{9}$$

The wear after 1 shot is determined according to the relationship between the specific energy and the wear resistance characteristics of the barrel metal [3]:

$$\frac{d(\Delta d)}{dN} = \frac{k_{sc}\xi}{8g} \int_{t_{cd}}^{t_d} \frac{\gamma_{kh} v_{kh}^3 dt}{\rho_T}. \tag{10}$$

Where: k_{sc} is the coefficient that takes into account the barrel wear in the final active period of the combustible gas [3]; t_d is the time that the bullet moves in the barrel; t_{cd} is the time that the combustible gas begins to affect the barrel; ρ_T is a characteristic of the wear resistance of the barrel metal:

$$\rho_T = k_\rho [1 - tanh(k_1 t_n)]. \tag{11}$$

k_1, k_ρ are the experimental coefficient [3];

$\tanh(k_1 t_n)$ is tang hyperbol function.

$$tanh(k_1 t_n) = \frac{e^{k_1 t_n} - e^{-k_1 t_n}}{e^{k_1 t_n} + e^{-k_1 t_n}}. \tag{12}$$

t_n is the temperature of the inner surface of the barrel; This value is determined by the problem of barrel heat, presented in section 3.1.

Radial wear affects the parameters of the system of interior ballistic equations through the following three quantities, see Fig. 3:

- The elongation of the combustion chamber ($\delta\lambda_1$);
- The distance crossed by the bullet from when the bullet is fired to when the belt is cut into the spiral groove ($\delta\lambda_2$);
- The largest area through which the burning gas flows (δs).

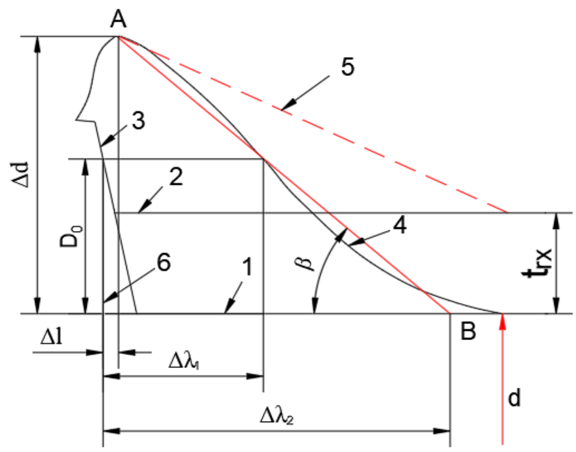

Fig. 3. Determination diagram $\delta\lambda_1, \delta\lambda_2, \delta s$ in terms of Δd [3]

The relationship between radial wear and the above three quantities is determined as follows [3]:

$$\delta\lambda_1 = \Delta d \cdot cot\,\beta \left(1 - \frac{D_0 - d}{\Delta d}\right), \tag{13}$$

$$\delta\lambda_2 = \Delta d \cdot cot\,\beta, \tag{14}$$

$$\delta s = \frac{\pi d}{2} \Delta d \left(1 - \frac{D_0 - d}{\Delta d}\right). \tag{15}$$

3.3 Establish the system of interior ballistic equations taking into account the barrel wear

The relationship between barrel wear and the bullet's velocity is determined through the interior ballistic problem. For gun barrels, the wear of the barrel will directly affect the ejection pressure, and the cutting of the belt at the spiral groove takes place after the warhead has moved a certain distance. So, the process of interior ballistic taking into account barrel wear is divided into two stages:

- The first stage: When the bullet is fired to when the centering belt is cut into the spiral groove.

- The second stage: Bullets move after the centering belt is cut into the spiral groove.

a. The first stage: When the bullet is fired to when the centering belt is cut into the spiral groove.

The distance of the projectile in this period is $\delta\lambda_2$. Because the land is worn, the bullet is not blocked by the land. Therefore, it can be considered that the bullet moves steadily faster due to the effect of the pressure force of burning gas $p{\cdot}S$. So, the velocity when the bullet cuts the land is determined by the formula [20-23]:

$$v_c = \sqrt{2{\cdot}a{\cdot}\delta\lambda_2} = \sqrt{2{\cdot}\frac{p.S}{q}{\cdot}\delta\lambda_2}. \quad (16)$$

The pressure when the bullet cuts the land is determined by the formula [4]:

$$p_0 = 4f_T\frac{H}{d'}\left[3000\left(0{,}1 + 1{,}1\frac{D_0 - d'}{d' - d_d}\right)^{0{,}6} + 550\right]\psi(\alpha_{rx}). \quad (17)$$

Where:

$$\psi(\alpha_{rx}) = \cos\alpha_{rx}\left[1 + \frac{\sin\alpha_{rx}\,(\sin\alpha_{rx} - f\cos\alpha_{rx})}{\cos\alpha_{rx} - f\sin\alpha_{rx}}\right].$$

f_T is the coefficient of friction between copper and steel; H is the width of ammunition guide belts; α_{rx} is the angle of inclination of the helix groove; D_0 is the diameter of the driving belt; d_d is the diameter of the bullet; d' is medium barrel caliber:

$$d' = \sqrt{\frac{4S}{\pi}}. \quad (18)$$

b. The second stage: Bullets move after the centering band is cut into the spiral groove.

At this stage, the interior ballistic equations are established with some assumptions as follows [8]:

- The rule of the firing rate of the propellant is determined by the formula $u = u_1{\cdot}p$;
- The combustion temperature of the burning gas is considered to be constant during the combustion process;
- The second work is calculated through the warhead's weight gain factor;
- Combustion product composition remains unchanged, quantities f and α also do not change.

The equation of motion of the bullet in the barrel [21-26]:

$$\begin{cases} \dfrac{\mathrm{dV}}{\mathrm{dt}} = \dfrac{\mathrm{s.p}}{\varphi.m}. \\ \dfrac{dl}{\mathrm{dt}} = V. \end{cases} \quad (19)$$

The combustion equation of the propellant [8]:

* The law of fire rate of propellant:

$$\frac{dz}{dt} = \frac{p}{I_k}. \quad (20)$$

* The law of changing the rate of gas generation:

$$\frac{d\omega_c}{dt} = \omega{\cdot}\chi(1 + 2{\cdot}z{\cdot}\lambda){\cdot}\frac{dz}{dt} - G_{\Delta d}. \quad (21)$$

The equation of the free volume of the combustion chamber [5]:

$$\frac{dW_\psi}{dt} = \left(\frac{1}{\delta} - \alpha\right){\cdot}\omega{\cdot}\frac{d\psi}{dt} + S_n{\cdot}\frac{dl}{dt}. \quad (22)$$

The equation of burning gas pressure in the barrel [5]:

$$\frac{dp}{dt} = \frac{1}{W_\psi}\left(f{\cdot}\omega\frac{d\psi}{dt} - K_T{\cdot}p - K_p{\cdot}p\frac{dW_\psi}{dt} - K_p < G_{\Delta d}\right). \quad (23)$$

Where: K_p is flow function; $G_{\Delta d}$ is the gas flow through the gap between the belt and barrel:

$$G_{\Delta d} = {\cdot}\Delta S{\cdot}A_1\sqrt{\frac{p.\omega_c}{W_\psi}}, \quad (24)$$

$$K_T = \frac{(k-1){\cdot}A{\cdot}v_1{\cdot}\sigma_T(F_k - \pi dl)}{R}, \quad (25)$$

$$v_1 = 1 - \frac{T_{tb}}{T}, \quad (26)$$

k is the adiabatic exponent; A is the thermomechanical equivalent; T_{tb} is the average temperature of the inner surface of the barrel; σ_t is heat transfer coefficient; F_k is the initial internal surface area of the ammunition chamber; d is the caliber of the barrel; l is the distance traveled by the bullet in the barrel; R is gas constant.

Combining the differential equations (20), (21), (22), (23), and (24), we get the system of interior ballistic differential equations including barrel wear as follows:

$$\begin{cases} \dfrac{dv}{dt} = \xi_3{\cdot}\dfrac{s}{\phi.m_d}{\cdot}p \\ \dfrac{dl}{dt} = \xi_3{\cdot}v \\ \dfrac{dz}{dt} = \xi_2{\cdot}\dfrac{P}{I_k} \\ \dfrac{d\omega}{dt} = \xi_2{\cdot}\omega{\cdot}(1 + 2{\cdot}\lambda{\cdot}z) \\ \dfrac{dW}{dt} = \xi_2{\cdot}\dfrac{1-\alpha.\delta}{\delta}{\cdot}\chi{\cdot}\omega(1 + 2\lambda{\cdot}z){\cdot}\dfrac{p}{I_k} + \xi_3{\cdot}s{\cdot}v \\ \dfrac{dp}{dt} = \left[f\dfrac{d\omega}{dt}{\cdot}g - \left(k_t + k\dfrac{dW}{dt}\right)\right]{\cdot}\dfrac{p}{W} \\ \dfrac{\partial T}{\partial\tau} = a\left(\dfrac{\partial^2 T}{\partial r^2} + \dfrac{1}{r}\dfrac{\partial T}{\partial r}\right) \\ \dfrac{d(\Delta d)}{dN} = \dfrac{k_{sc}\xi}{8g}\displaystyle\int_{t_{cd}}^{t_d}\dfrac{\gamma_{kh}v_{kh}^3 dt}{\rho_T} \end{cases} \quad (27)$$

The system of differential equations (27) is solved simultaneously with equation (10) using the initial conditions: $v[1] = v_c$; $l[1] = \delta\lambda_2$; $t[1] = t_c$; $p[1] = p_0$, $\Delta d[1] = 0$, the radial wear Δd is determined, (according to Fig. 3). Matlab software is used to solve the above system of equations according to the algorithm diagram in Fig. 4.

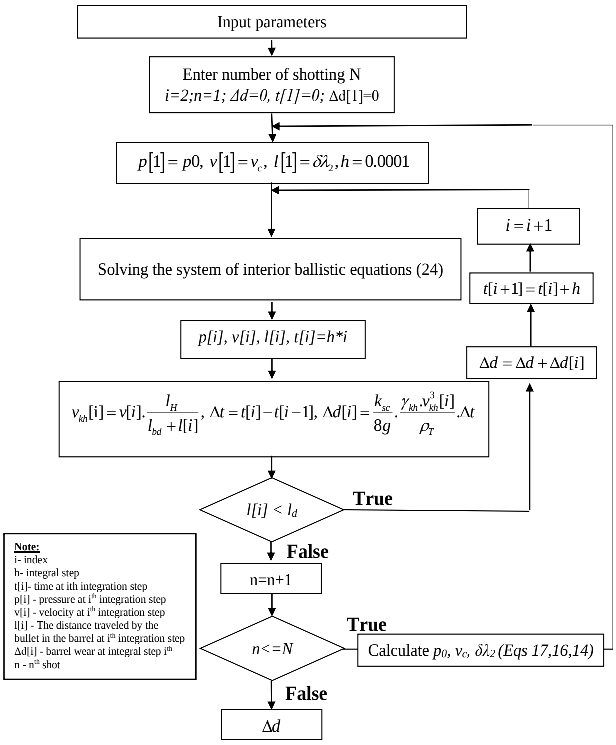

Fig. 4. Algorithm used to solve the system of interior ballistic equations with barrel wear

4. RESULTS AND DISCUSSION

4.1 Calculational results for new test barrel

The test gun was manufactured to test the bullet's characteristics such as muzzle velocity, and maximum pressure for 7.62x25mm bullets. So, the reduction in muzzle bullet velocity due to barrel wear has an important effect on the accuracy of the test. The structure parameters of the 7.62x25mm test gun is shown in Fig. 5 and Table 1.

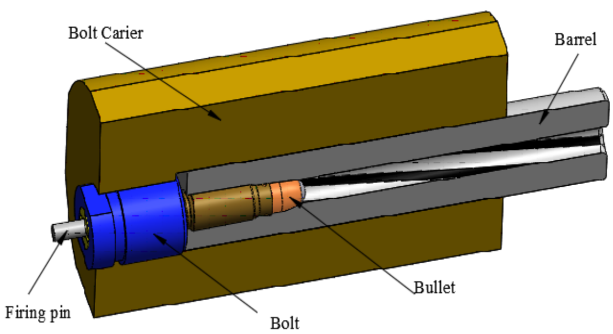

Fig. 5. Structure of the 7.62x25mm test gun

Table 1. Structural parameters of the test gun and the 7.62x25mm bullet [4]

Parameters	Units	Value
The cross-sectional area of barrel	m^2	$4.761 \cdot 10^{-5}$
Combustion chamber volume	m^3	$0.93 \cdot 10^{-6}$
The length of the distance the bullet travels in the original barrel	m	0.087
Weight of the warhead	N	$55 \cdot 10^{-3}$
Initial ejection pressure	MPa	11.77
Weight of propellant	N	$49.05 \cdot 10^{-4}$
Powder force	Nm/N	95000
Density of propellant	kg/m^3	1600
The total impetus of the burning gas pressure	Ns/m^3	515025
Adiabatic exponent	-	1.2
Coefficient of secondary works account	-	1.118
The angle of inclination of the helix groove	deg	6
Groove depth	m	$0.3 \cdot 10^{-3}$
Diameter of driving belt	m	$7.82 \cdot 10^{-3}$
Caliber of bullet	m	$7.62 \cdot 10^{-3}$
Distance from the bottom of the combustion chamber to the top of the rifle	m	$28.84 \cdot 10^{-3}$
Width of bullet's driving belts	m	$5 \cdot 10^{-3}$
Coefficient of friction between copper and steel	-	0.25
The coefficient that takes into account the barrel wear in the final active period of the combustible gas	-	1.1

The results of solving the interior ballistic problem and the problem of barrel heat for the test gun when firing the first shot are shown in Figs. 6, 7, and 8.

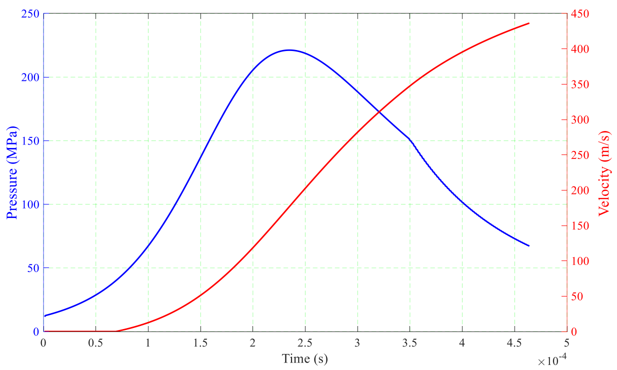

Fig. 6. Graph of pressure and velocity over time

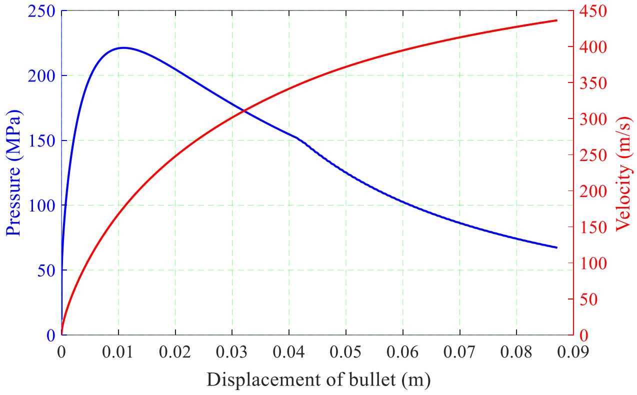

Fig. 7. Graph of pressure and velocity over time

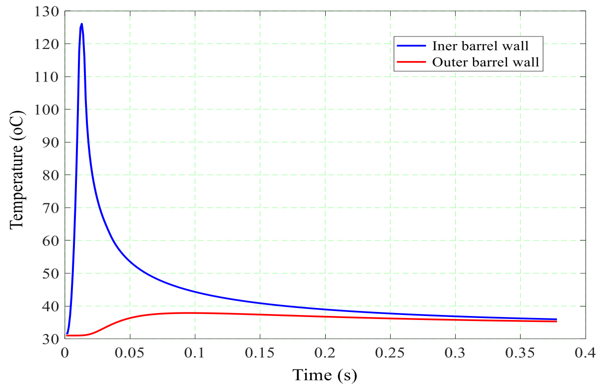

Fig. 8. Graph of inner and outer wall temperature of the barrel

4.2 Determination of barrel wear parameters according to the number of firing

The barrel wear parameters on the 7.62x25mm bullet test gun were determined with the number of firing N being 1, 1000, 2000, 3000, 4000, 5000, 6000. This parameter is large enough to determine the service life of the test gun after a period of working.

The results are shown in Table 2. The results of Table 2 show:

- Radial barrel wear Δd increases significantly with a large number of firing. This barrel wear directly affects the interior ballistic process and the condition of the driving belt cutting. Table 2 shows that the belt cutting pressure decreased by 5.7% when firing the first 1000 rounds and decreased by 30.1% when firing 6000 rounds.

- Barrel wear creates distance $\Delta\lambda_2$, which the bullet crosses before cutting the belt. Therefore, the velocity of the warhead is non-zero when cutting the driving belt.

Table 2. Calculation results of barrel wear

	Barrel wear corresponds to N shots						
	1	1000	2000	3000	4000	5000	6000
$\Delta d \cdot 10^{-3}$, (m)	0.00033	0.334	0.668	1.002	1.337	1.671	2.005
$\delta\lambda_1 \cdot 10^{-3}$, (m)	0	0.201	0.702	1.204	1.705	2.207	2.708
$\delta\lambda_2 \cdot 10^{-3}$,m	0.00050	0.501	1.002	1.504	2.005	2.507	3.008
$\delta S \cdot 10^{-9}$, (m²)	0	0.016	0.056	0.096	0.136	0.176	0.216
p_0, (MPa)	39.5	37.2	35.1	33.0	31.1	29.3	27.6

4.3 Investigate the effect of barrel wear on the muzzle velocity of 7.62x25mm bullet

The results of solving the interior ballistic problem with barrel wear are presented in Figs. 9 - 10 and Table 3.

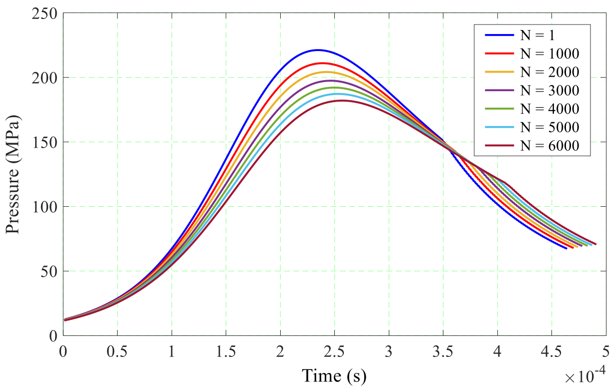

Fig. 9. Graph of pressure corresponding to the time

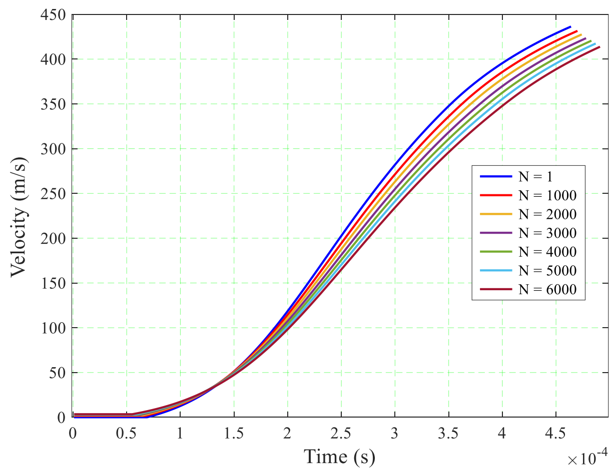

Fig. 10. Graph of velocity corresponding to the time

Table 3. Muzzle velocity of the bullet

Number of firing	Muzzle bullet velocity v_0 (m/s)	$\frac{\Delta v_{0i}-\Delta v_{01}}{v_{01}}$ (%)
1	436	0
1000	431	1.15
2000	427	2.06
3000	423	2.98
4000	420	3.67
5000	417	4.36
6000	413	5.28

Fig. 9 shows that the interior ballistic pressure over time has changed markedly with the increase in the number of shots.

- The maximum pressure is reduced by 4.5% when firing 1000 rounds and 17.69% when firing 6000 rounds.

- The time it takes for the propellant to run out has been increased. This is also consistent with the fact that the combustion pressure is reduced.

In fact, one of the most important factors when assessing barrel life is muzzle bullet velocity. For test guns, this quantity is of even greater interest. Table 3 and Fig. 10 show: The muzzle bullet velocity decreases significantly after a certain number of fires. After firing with the number of fire of 1000, 2000, 3000, 4000, 5000, and 6000 respectively, the muzzle bullet velocity decreases by 1.15%, 2.06%, 2.98%, 3.67%, 4.36%, and 5.28% respectively. So if 5% is taken as a comparison to evaluate the life of the test gun, after 5000 fires, the barrel needs to be replaced [26].

5. CONCLUSION

The purpose of the paper is to establish a system of interior ballistic equations taking into account the wear of the barrel when series firing by the theoretical method. Based on the investigated results, the following conclusions are drawn.

- The barrel wear is an important quantity that determines the life of the gun barrel. Barrel wear causes a change in the reaction force between the driving belt and the barrel surface, which is the cause of the reduction in the belt cutting pressure p_0. According to Table 2, this value decreased from 39.5 MPa to 27.6 MPa after 6000 shots.

- Barrel wear increases the clearance between the bullet belt and the barrel, and the air discharge is increased. As a result, in Table 3, bullet velocity is reduced by 5.28% after firing 6000 rounds [26].

- For test guns, the reduction in the velocity of the warhead directly affects the measurement results. So, before making a measurement, it is necessary to carefully consider the number of shots taken to evaluate the error accordingly.

Although it is possible for the conclusion to contain the main points of the paper, do not repeat the abstract as a conclusion. The conclusion may emphasize the significance of the paper, its application, and further research possibilities.

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