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Recoilless Gun System as a Particular Form of General Interior Ballistics Model of Gun Propellant Systems

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Abstract. The development of the interior ballistics general model of gun propellant systems by taking into account the specificity of the recoilless propellant system is presented in this paper. The presented expanded physical and mathematical model makes possible the simulation of classical and nonclassical gun systems: two-chamber, mortar, and the considered recoilless one. To solve the system of equations associated with the mathematical model, a computer programme was developed. An analysis was made for two configurations of a recoilless system, differing in the way of arrangement of a propellant charge, i.e., with the propellant charge moving together with a projectile and with the propellant charge burning in a cartridge chamber. The obtained calculation results showed that the system, in which the propellant charge moves together with a projectile, has the maximum pressure and the muzzle velocity higher in comparison with the system with the propellant charge burning in a cartridge chamber. Influence of a way of placement of the propellant charge is the stronger, the higher is the ratio of its mass to the projectile mass.

The results of the accomplished calculations, especially the pressure inside the barrel as well as motion parameters of the projectile make the grounds for projecting and construction optimization of the recoilless gun systems.
Keywords: mechanics, interior ballistics, recoilless propellant system

1. INTRODUCTION

A propellant gun system is used, among others, to give the projectile a determined muzzle velocity ensuring the required range and accuracy of fire. One of many kinds of propellant gun systems is considered here – it is a recoilless system. Such a system is applied, among others, in hand-held, anti-tank grenade launchers and in recoilless guns.

Due to opening a barrel slot, the ejection of propellant combustion products from a chamber volume of a gun system, e.g., through a nozzle at the rear end of the weapon, creates a force that is directed opposite to a gun rearward thrust. As a result, the recoil force is eliminated or significantly reduced what ensures recoilless character of a shot process. Another method to eliminate gun recoil is to apply, so-called, backward mass [1, 2]. Recoilless character of gun work allows us to construct lighter weapon and in a case of hand held, anti-tank grenade launchers to make off-hand shooting.

When designing the weapon, including weapon with a recoilless propellant system, ballistic characteristics of weapon, especially the pressure of propellant gases and projectile velocity in a barrel bore are used. These characteristics are obtained as a result of solution of, so-called, main problem of internal ballistics (MPIB), i.e., solution of a system of equations describing physical phenomena occurring in a barrel of propellant system during the shot. Exemplary ballistic characteristics of recoilless systems obtained with simplifying assumptions allowing for analytical solution, are presented in work [3]. A mathematical-physical model of the recoil propellant system operation can be built using interior ballistics laws [3, 4], taking into account the specific operation and characteristics of the considered system as well as individual parameters of the propellant charge.

The paper presents physical and mathematical model of gun propellant systems which is an extended general model [5] including the considered recoilless system. To formulate the equations, thermodynamic approach has been applied, earlier presented in the works on simulation of operation of gun propellant systems [5, 6, 7, 8]. As a result of numerical solution of the given model, with taken into consideration specificity of recoilless system, the basic ballistic characteristics have been obtained, i.e., the pressure of propellant gases p in a chamber volume of gun system and the velocity V of a projectile as a function of the time t or the projectile displacement l.

2. PHYSICAL MODEL OF THE RECOILLESS PROPELLANT SYSTEM

Schematic and characteristic elements of the recoilless system are shown in Fig. 1.

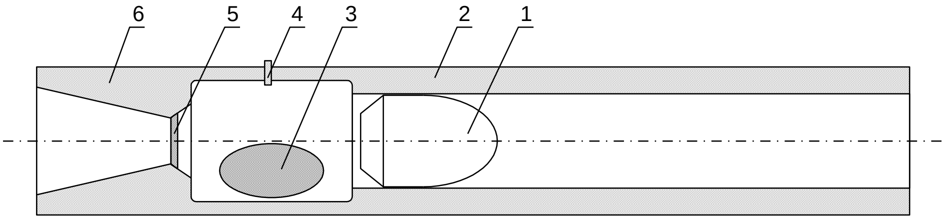

Fig. 1. Schematic of the recoilless propellant system:
1 – projectile, 2 – barrel, 3 – propellant, 4 – igniter, 5 – closure, 6 – nozzle

The system operation (shot) starts from actuation of the igniter (4) and the beginning of propellant combustion (3). The propellant (3) burns initially in a closed chamber volume of a gun system. Increase in pressure of combustion products causes, on the one hand, the movement of a projectile in a barrel and on the other hand ejection of the closure (5) and opening a barrel intake (nozzle). Outflow of a part of propellant gases through the nozzle (6) in opposite direction to the projectile movement creates a force that compensates (for adequate construction of a system) other forces influencing the propellant system (weapon). Recoilless character of operation of the considered system is possible when a projectile movement starts at the moment of closure ejection.

The considered here recoilless system can be a special form of a general model of internal ballistics of the gun propellant systems that is shown in Fig. 2.

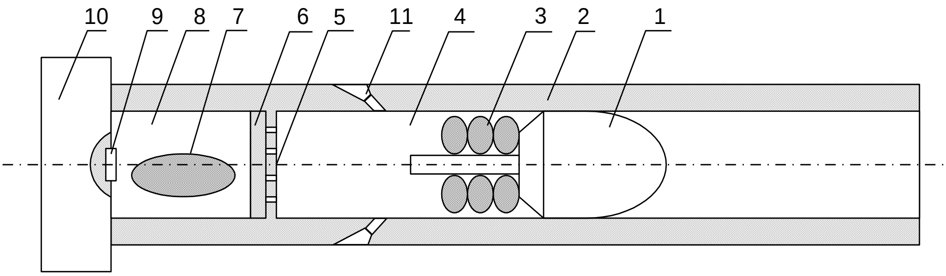

Fig. 2. Schematic of the general propellant system:
1 – projectile, 2 – barrel, 3 – propellant *II*, 4 – chamber *II*, 5 – partition, 6 – membrane, 7 – propellant *I*, 8 – chamber *I*, 9 – igniter, 10 – breechblock, 11 – nozzle

A scheme shown in Fig. 2 is a generalized scheme of four propellant gun systems, specific due to construction and principle of operation: classical, two-chamber, mortar, and recoilless ones.

In dependence on the elements that we eliminate from the scheme in Fig. 2, we obtain one of the above mentioned propellant systems. An analysis of mortar, two-chamber, and classical systems, being the special forms of a general propellant system is given in the work [5].

The considered here recoilless system can be obtained by elimination from a general scheme (Fig. 2) the propellant *I* (7) and the partition (5) with the membrane (6). Such a configuration (Fig. 3a) with the connected propellant charge (moving) with the projectile during a shot process is used, e.g., in hand held, anti-tank grenade launchers.

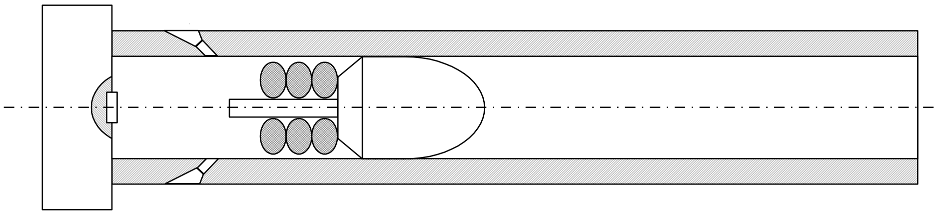

Fig. 3a. Schematic of the recoilless propellant system with the propellant connected to the projectile

Another configuration of a recoilless system (Fig. 3b), with propellant charge that is not connected (not moving) with a projectile during a shot process, is used, e.g., in heavy grenade launchers (recoilless guns).

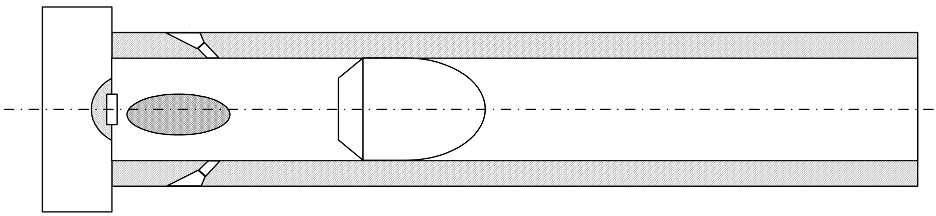

Fig. 3b. Schematic of the recoilless propellant system with not moving propellant

For the scheme of a general propellant system (Fig. 2) there have been formulated the equations describing phenomena occurring in this system during a shot process. The formulated system of equations is a general mathematical model MPIB of the being analysed gun propellant systems in thermodynamic approach. Solution of this model, with taking into account the specificity of construction and operation of a recoilless system, will give the information on parameters of its work, among others, the pressure of propellant gases $p(t)$ in a barrel bore and the projectile velocity $V(t)$.

3. MATHEMATICAL MODEL OF THE GENERAL PROPELLANT SYSTEM

Having in view the specificity of the construction of a general propellant system (Fig. 2), especially the division of behind-projectile space (combustion chamber) into two chambers, the equations of the mathematical model MPIB have been formulated in reference to both chambers. For formulation of these equations, two possible directions of flow of propellant gases have been considered, i.e., flow from the chamber *I* to the chamber *II* and flow from the chamber *II* to the chamber *I*. The phenomena that take place during a propellant system operation can be described using the fundamental laws of mechanics and thermodynamics, taking into account the specific operation of the considered system. To obtain a complete picture of the internal ballistics cycle of the considered general system, the mathematical model centered on balance of energy (thermodynamic model) was worked out. In constructing the model, the major assumptions were used:

- grains of the specified propellant charge are all of the same geometrical, physical and chemical configuration. All propellant charge grains have been ignited simultaneously, with all exposed surface areas. All grains recede at the uniform rate and have constant shape during a burning process;
- composition and properties of propellant gases, such as specific heat ratio, specific gas constant and covolume are not changing during a firing cycle;
- the specific heat ratio k and the specific gas constant R are identical for both propellant charges (*I* and *II*);
- the considered thermodynamic processes are adiabatic, the outflow (from the barrel) and the flow (between the chamber *I* and chamber *II*) of propellant gases are quasi-steady;
- secondary works of propellant gases are expressed using the secondary works (energy-loss) coefficient φ: constant for classical system and changeable for nonclassical systems, taking into account the real mass (kinetic energy) of gases and unburned propellant grains moving behind the projectile [3, 4, 9];
- additional force acted on the projectile, resulting from the change of mass of the burning propellant charge (*II*) connected to the projectile, is neglected.

The symbols appearing in the equations of the mathematical model of the operation of a general propellant system are:

c_p – specific heat at constant pressure
c_v – specific heat at constant volume
F_m – minimum cross-section area of nozzle
F_p – cross-section area of flow of gas between the chambers *I* and *II*

I_I – enthalpy of gas created from combustion of propellant *I*, flowing out of the chamber *I* into the chamber *II* or flowing out of the chamber *II* into the chamber *I*

I_{II} – enthalpy of gas created from combustion of the propellant *II*, flowing out of the chamber *I* into the chamber *II* or flowing out of the chamber *II* into the chamber *I*

I_d – enthalpy of gas flowing out of the chamber *II* through nozzle

I_n – enthalpy of gas flowing out of the chamber *II* through gap between projectile and barrel

k – ratio of specific heats (adiabatic exponent)

K – constant of coefficient of secondary works of propellant gas

l – projectile travel inside a barrel

L – sum of works of propellant gas

m – mass of a projectile

n_I, n_{II} – burning rate index of the propellant *I* and *II*, respectively

p_I, p_{II} – pressure in the chamber *I* and *II*, respectively

Q_I, Q_{II} – energy from combustion of the propellant *I* and *II*, respectively

q_{sI}, q_{sII} – heat of explosion of the propellant *I* and *II*, respectively

R – specific propellant gas constant

s – cross-section area of a bore

s_n – cross-section area of a gap between a projectile and a barrel

s_p – maximum cross-section area of a projectile

S_{1I}, S_{1II} – initial surface of grain of the propellant *I* and *II*, respectively

t – time

T_n – initial temperature

T_{1I}, T_{1II} – isochoric flame temperature of the propellant *I* and *II*, respectively

T_I, T_{II} – temperature of propellant gas inside the chamber *I* and *II*, respectively

U_I, U_{II} – energy of propellant gas inside the chamber *I* and *II*, respectively

V – velocity of a projectile

W_I, W_{II} – initial volume (no propellant) of the chamber *I* and *II*, respectively

α_I, α_{II} – gas covolume of the propellant *I* and *II*, respectively

β_I, β_{II} – burning rate coefficient of the propellant *I* and *II*, respectively

δ_I, δ_{II} – density of the propellant *I* and *II*, respectively

ζ_d – correction factor of gas flowing out of the chamber *II* through nozzle

ζ_n – correction factor of gas flowing out of the chamber *II* through gap between projectile and barrel

ζ_p – correction factor of gas flowing through the chambers *I* and *II*

η_I – relative mass of the propellant *I* in gas form, which flew out of the chamber *I* into the chamber *II*

η_{II} – relative mass of the propellant *II* in gas form, which flew out of the chamber *II* into the chamber *I*

η_d – relative mass of the propellants *I* and *II* in gas form, which flew out of the chamber *II* through nozzle

η_n – relative mass of the propellants *I* and *II* in gas form, which flew out of the chamber *II* through gap between projectile and barrel
χ_{1I}, λ_{1I} – shape coefficients of the propellant *I* grain
χ_{1II}, λ_{1II} – shape coefficients of the propellant *II* grain
φ – coefficient of secondary works
ψ_I, ψ_{II} – relative amount of burned the propellant *I* and *II*, respectively
ω_I, ω_{II} – mass of propellant *I* and *II* respectively
Λ_{1I}, Λ_{1II} – initial volume of grain of the propellant *I* and *II*, respectively.

For the chamber *I*, the energy conservation equation:

– for the flow of gases from the chamber *I* to the chamber *II* takes the form:

$$dU_I = dQ_I - dI_I - dI_{II} \tag{1a}$$

considering that:

$$dU_I = d\left[\left(c_v\omega_I\left(\psi_I - \eta_I\right) + c_v\omega_{II}\eta_{II}\right)T_I\right]$$

$$dQ_I = d\left(c_v\left(T_{1I} - T_n\right)\omega_I\psi_I\right) = q_{sI}\omega_I d\psi_I$$

$$dI_I = d\left(c_p T_I \omega_I \eta_I\right) = c_p T_I \omega_I d\eta_I$$

$$dI_{II} = -d\left(c_p T_I \omega_{II}\eta_{II}\right) = -c_p T_I \omega_{II} d\eta_{II}$$

we obtain the energy balance in the form:

$$\frac{dRT_I}{dt} = \frac{\left(\left(k-1\right)q_{sI} - RT_I\right)\omega_I \dfrac{d\psi_I}{dt} - \left(k-1\right)RT_I\omega_I \dfrac{d\eta_I}{dt} + \left(k-1\right)RT_I\omega_{II}\dfrac{d\eta_{II}}{dt}}{\omega_I\left(\psi_I - \eta_I\right) + \omega_{II}\eta_{II}} \tag{1b}$$

– for the flow of gases from the chamber *II* to the chamber *I* takes the form:

$$dU_I = dQ_I + dI_I + dI_{II} \tag{1c}$$

considering the changes of enthalpy definition:

$$dI_I = -d\left(c_p T_{II}\omega_I\eta_I\right) = -c_p T_{II}\omega_I d\eta_I$$

$$dI_{II} = d\left(c_p T_{II}\omega_{II}\eta_{II}\right) = c_p T_{II}\omega_{II} d\eta_{II}$$

we obtain the energy balance in the form:

$$\frac{dRT_I}{dt} = \frac{\left(\left(k-1\right)q_{sI} - RT_I\right)\omega_I \dfrac{d\psi_I}{dt} - \left(kRT_{II} - RT_I\right)\left(\omega_I \dfrac{d\eta_I}{dt} - \omega_{II}\dfrac{d\eta_{II}}{dt}\right)}{\omega_I\left(\psi_I - \eta_I\right) + \omega_{II}\eta_{II}} \tag{1d}$$

Other relationships relating to the chamber *I* are:
– equation of state of propellant gases

$$p_I\left(W_I-\frac{\omega_I}{\delta_I}(1-\psi_I)-\alpha_I\omega_I(\psi_I-\eta_I)-\alpha_{II}\omega_{II}\eta_{II}\right)=RT_I(\omega_I(\psi_I-\eta_I)+\omega_{II}\eta_{II}) \quad (2)$$

– mass of gas generated by combustion of propellant *I* [3]

$$\frac{d\psi_I}{dt}=\frac{S_{1I}}{\Lambda_{1I}}\sqrt{1+4\frac{\lambda_{1I}}{\chi_{1I}}\psi_I}\cdot\beta_I p_I^{n_I} \quad (3)$$

– equations of propellant gases flowing out of the chamber *I* into the chamber *II* [10, 11]

$$\frac{d\eta_I}{dt}=\frac{\zeta_p F_p}{\omega_I}\left(\frac{2}{k+1}\right)^{\frac{1}{k-1}}\sqrt{\frac{2k}{k+1}}\frac{p_I}{\sqrt{RT_I}} \quad \text{if} \quad \frac{p_{II}}{p_I}\le\left(\frac{2}{k+1}\right)^{\frac{k}{k-1}} \quad (4)$$

or $$\frac{d\eta_I}{dt}=\frac{\zeta_p F_p}{\omega_I}\sqrt{\frac{2k}{k-1}\left[\left(\frac{p_{II}}{p_I}\right)^{\frac{2}{k}}-\left(\frac{p_{II}}{p_I}\right)^{\frac{k+1}{k}}\right]}\frac{p_I}{\sqrt{RT_I}} \quad \text{if} \quad \frac{p_{II}}{p_I}>\left(\frac{2}{k+1}\right)^{\frac{k}{k-1}} \quad (4a)$$

$$\frac{d\eta_{II}}{dt}=-\frac{\zeta_p F_p}{\omega_{II}}\left(\frac{2}{k+1}\right)^{\frac{1}{k-1}}\sqrt{\frac{2k}{k+1}}\frac{p_I}{\sqrt{RT_I}} \quad \text{if} \quad \frac{p_{II}}{p_I}\le\left(\frac{2}{k+1}\right)^{\frac{k}{k-1}} \quad (5)$$

or $$\frac{d\eta_{II}}{dt}=-\frac{\zeta_p F_p}{\omega_{II}}\sqrt{\frac{2k}{k-1}\left[\left(\frac{p_{II}}{p_I}\right)^{\frac{2}{k}}-\left(\frac{p_{II}}{p_I}\right)^{\frac{k+1}{k}}\right]}\frac{p_I}{\sqrt{RT_I}} \quad \text{if} \quad \frac{p_{II}}{p_I}>\left(\frac{2}{k+1}\right)^{\frac{k}{k-1}} \quad (5a)$$

For the chamber *II*, the energy conservation equation:
– for the flow of gases from the chamber *I* to the chamber *II* takes the form:

$$dU_{II}=dQ_{II}+dI_I+dI_{II}-dI_d-dI_n-dL \quad (6a)$$

considering that:

$$dU_{II}=d\left[\left(c_v\omega_{II}(\psi_{II}-\eta_{II}-\eta_d-\eta_n)+c_v\omega_I(\eta_I-\eta_d-\eta_n)\right)T_{II}\right]$$

$$dQ_{II}=d\left(c_v(T_{1II}-T_n)\omega_{II}\psi_{II}\right)=q_{sII}\omega_{II}d\psi_{II}$$

$$dI_I=d\left(c_pT_I\omega_I\eta_I\right)=c_pT_I\omega_I d\eta_I$$

$$dI_{II}=-d\left(c_pT_I\omega_{II}\eta_{II}\right)=-c_pT_I\omega_{II}d\eta_{II}$$

$$dI_d = d\left(c_p T_{II}\left(\omega_I + \omega_{II}\right)\eta_d\right) = c_p T_{II}\left(\omega_I + \omega_{II}\right)d\eta_d$$

$$dI_n = d\left(c_p T_{II}\left(\omega_I + \omega_{II}\right)\eta_n\right) = c_p T_{II}\left(\omega_I + \omega_{II}\right)d\eta_n$$

$$dL = d\left(\varphi\left(m + \omega_{II}\left(1-\psi_{II}\right)\right)\frac{V^2}{2}\right)$$

where $\varphi = K + \dfrac{1}{3}\dfrac{\omega_I\left(\eta_I - \eta_d - \eta_n\right) + \omega_{II}\left(\psi_{II} - \eta_{II} - \eta_d - \eta_n\right)}{m + \omega_{II}\left(1-\psi_{II}\right)}$

we have the energy balance in the form:

$$\frac{d}{dt}\left[RT_{II}\left(\omega_{II}\left(\psi_{II} - \eta_{II} - \eta_d - \eta_n\right) + \omega_I\left(\eta_I - \eta_d - \eta_n\right)\right)\right] = (k-1)q_{sII}\omega_{II}\frac{d\psi_{II}}{dt} + kRT_I\left(\omega_I\frac{d\eta_I}{dt} - \omega_{II}\frac{d\eta_{II}}{dt}\right) + \qquad \text{(6b)}$$
$$-kRT_{II}\left(\omega_I + \omega_{II}\right)\left(\frac{d\eta_d}{dt} + \frac{d\eta_n}{dt}\right) +$$
$$-(k-1)\left(\frac{d\varphi}{dt}\left(\left(m + \omega_{II}\left(1-\psi_{II}\right)\right)\frac{V^2}{2}\right) + \varphi\left(-\omega_{II}\frac{d\psi_{II}}{dt}\frac{V^2}{2} + \left(m + \omega_{II}\left(1-\psi_{II}\right)\right)V\frac{dV}{dt}\right)\right)$$

– for the flow of gases from the chamber *II* to the chamber *I* takes the form:

$$dU_{II} = dQ_{II} - dI_I - dI_{II} - dI_d - dI_n - dL \qquad \text{(6c)}$$

considering the changes of enthalpy definition:

$$dI_I = -d\left(c_p T_{II}\omega_I\eta_I\right) = -c_p T_{II}\omega_I d\eta_I$$

$$dI_{II} = d\left(c_p T_{II}\omega_{II}\eta_{II}\right) = c_p T_{II}\omega_{II} d\eta_{II}$$

we have the energy balance in the form:

$$\frac{d}{dt}\left[RT_{II}\left(\omega_{II}\left(\psi_{II} - \eta_{II} - \eta_d - \eta_n\right) + \omega_I\left(\eta_I - \eta_d - \eta_n\right)\right)\right] = (k-1)q_{sII}\omega_{II}\frac{d\psi_{II}}{dt} + kRT_{II}\left(\omega_I\frac{d\eta_I}{dt} - \omega_{II}\frac{d\eta_{II}}{dt}\right) + \qquad \text{(6d)}$$
$$-kRT_{II}\left(\omega_I + \omega_{II}\right)\left(\frac{d\eta_d}{dt} + \frac{d\eta_n}{dt}\right) +$$
$$-(k-1)\left(\frac{d\varphi}{dt}\left(\left(m + \omega_{II}\left(1-\psi_{II}\right)\right)\frac{V^2}{2}\right) + \varphi\left(-\omega_{II}\frac{d\psi_{II}}{dt}\frac{V^2}{2} + \left(m + \omega_{II}\left(1-\psi_{II}\right)\right)V\frac{dV}{dt}\right)\right)$$

Other relationships related to the chamber *II* are:
– equation of state of propellant gases in the chamber *II*

$$p_{II}\left(W_{II} + sl - \frac{\omega_{II}}{\delta_{II}}\left(1-\psi_{II}\right) - \alpha_I\omega_I\left(\eta_I - \eta_d - \eta_n\right) - \alpha_{II}\omega_{II}\left(\psi_{II} - \eta_{II} - \eta_d - \eta_n\right)\right) = \qquad \text{(7)}$$
$$RT_{II}\left(\omega_I\left(\eta_I - \eta_d - \eta_n\right) + \omega_{II}\left(\psi_{II} - \eta_{II} - \eta_d - \eta_n\right)\right)$$

– mass of gas generated by combustion of the propellant *II*

$$\frac{d\psi_{II}}{dt} = \frac{S_{1II}}{\Lambda_{1II}} \sqrt{1 + 4\frac{\lambda_{1II}}{\chi_{1II}}\psi_{II}} \cdot \beta_{II} p_{II}^{nII} \tag{8}$$

– equations of propellant gases flowing out of the chamber *II* into the chamber *I*

$$\frac{d\eta_I}{dt} = -\frac{\zeta_p F_p}{\omega_I}\left(\frac{2}{k+1}\right)^{\frac{1}{k-1}} \sqrt{\frac{2k}{k+1}} \frac{p_{II}}{\sqrt{RT_{II}}} \quad \text{if} \quad \frac{p_I}{p_{II}} \le \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}} \tag{9}$$

or
$$\frac{d\eta_I}{dt} = -\frac{\zeta_p F_p}{\omega_I} \sqrt{\frac{2k}{k-1}\left[\left(\frac{p_I}{p_{II}}\right)^{\frac{2}{k}} - \left(\frac{p_I}{p_{II}}\right)^{\frac{k+1}{k}}\right]} \frac{p_{II}}{\sqrt{RT_{II}}} \quad \text{if} \quad \frac{p_I}{p_{II}} > \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}} \tag{9a}$$

$$\frac{d\eta_{II}}{dt} = \frac{\zeta_p F_p}{\omega_{II}}\left(\frac{2}{k+1}\right)^{\frac{1}{k-1}} \sqrt{\frac{2k}{k+1}} \frac{p_{II}}{\sqrt{RT_{II}}} \quad \text{if} \quad \frac{p_I}{p_{II}} \le \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}} \tag{10}$$

or
$$\frac{d\eta_{II}}{dt} = \frac{\zeta_p F_p}{\omega_{II}} \sqrt{\frac{2k}{k-1}\left[\left(\frac{p_I}{p_{II}}\right)^{\frac{2}{k}} - \left(\frac{p_I}{p_{II}}\right)^{\frac{k+1}{k}}\right]} \frac{p_{II}}{\sqrt{RT_{II}}} \quad \text{if} \quad \frac{p_I}{p_{II}} > \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}} \tag{10a}$$

– equations of propellant gases flowing out of the chamber *II* through the nozzle

$$\frac{d\eta_d}{dt} = \frac{\zeta_d F_m}{\omega_I + \omega_{II}}\left(\frac{2}{k+1}\right)^{\frac{1}{k-1}} \sqrt{\frac{2k}{k+1}} \frac{p_{II}}{\sqrt{RT_{II}}} \tag{11}$$

– equations of propellant gases flowing out of the chamber *II* through the gap between a projectile and a barrel

$$\frac{d\eta_n}{dt} = \frac{\zeta_n s_n}{\omega_I + \omega_{II}}\left(\frac{2}{k+1}\right)^{\frac{1}{k-1}} \sqrt{\frac{2k}{k+1}} \frac{p_{II}}{\sqrt{RT_{II}}} \tag{12}$$

– equation of the projectile motion

$$\frac{dV}{dt} = \frac{p_{II} s_p}{\varphi\left[m + \omega_{II}\left(1 - \psi_{II}\right)\right]} \tag{13}$$

– definition of the projectile velocity

$$\frac{dl}{dt} = V \tag{14}$$

4. SPECIFICITY OF THE RECOILLESS PROPELLANT SYSTEM

In the considered recoilless system (Figs. 3a and 3b) there is one propellant burning in one chamber, so-called behind-projectile space. According to the denotations taken for a general system (Fig. 2), burning of the propellant charge *II* proceeds in the combustion chamber *II*. Denotation of main characteristics of recoilless system is shown in Fig. 4.

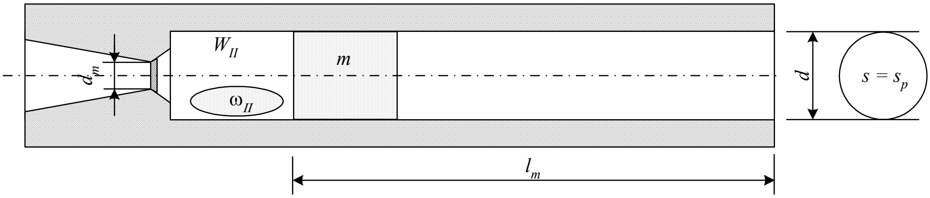

Fig. 4. Ballistic model and nomenclature of a recoilless system:
d – caliber, d_m – minimum diameter of nozzle, l_m – length of barrel

Because of one-chamber construction of the behind-projectile space of the recoilless system, there are no inter-chamber flows of powder gases. Moreover, in this system, practically there is no outflow of gases ahead the projectile ($s = s_p$). Taking into account the above ($\omega_I = 0$, $W_I = 0$, $F_p = 0$, $s_n = 0$), there will not be used equations 1÷5 and 9, 10, 12 ($\dot{\psi}_I = \dot{\eta}_I = \dot{\eta}_{II} = \dot{\eta}_n = 0$ and $\psi_I = \eta_I = \eta_{II} = \eta_n = 0$), and equations 6 and 7 will be simplified. Moreover, for the system in which the propellant does not move together with the projectile (Fig. 3b), in d*L* component of the energy balance (6), in equation of projectile motion (13) and in the coefficient of secondary works φ we will take into account $\omega_{II}(1-\psi_{II})=0$. Finally, the coefficient φ for the system in which propellant charge burning in a cartridge chamber takes the form [3]

$$\varphi = K + \frac{1}{3}\frac{\omega_{II}(1-\eta_d)}{m} \tag{15}$$

The secondary works are considered in similar way in work [4]. Using the symbols adopted in the article, the coefficient φ takes the form

$$\varphi = K + \frac{1}{2}\kappa\frac{\omega_{II}(1-\eta_d)}{m} \tag{16}$$

where: κ – semi-empirical coefficient ($\kappa < 1$). Values of the coefficient φ calculated from formulas (15) and (16) can be very similar practically.

Shot phenomenon in a recoilless system can be conventionally divided into two characteristic periods: pyrostatic and pyrodynamic ones. In a pyrostatic period there proceeds ignition and burning of the propellant charge *II* in the initially constant and closed volume of the combustion chamber *II*.

At the moment when the propellant gases in the chamber *II* reach so-called the shot start pressure p_{II0}, the pyrodynamic period starts which lasts till the projectile exit. In this period, there occur simultaneously the phenomena of driving the projectile and flowing out the gases through the nozzle. In the pyrodynamic period, one can distinguish two sub-periods, which are separated by the moment of the propellant charge burnout. For the pyrostatic period, the initial conditions for calculations are the following:

$$t = 0,\ \psi_{II} = \psi_i,\ \eta_d = 0,\ l = 0,\ V = 0,\ RT_{II} = f_{II},$$

where: f_{II} is the force of the propellant charge *II*.

Initial conditions for the pyrodynamic period constitute the final results that are obtained from the pyrostatic period.

In order to solve the equations of the mathematical model as presented in Section 3, the computer programme was developed. The fourth-order Runge-Kutta numerical method was applied for the solution of the ordinary first-order differential equations. Figures 5-7 present the charts of main shot characteristics obtained from MPIB solution of the recoilless system of 73 mm bore for two alternatives of the propellant charge placement. For numerical simulations, the following data were taken: m = 2.5 kg, ω_{II} = 1.0 kg, W_{II} = 2 dm^3, l_m = 0.85 m, $s = s_p$ = 4185 mm^2, d_m = 57 mm, K = 1, ζ_d = 0.90 and the properties of the propellant charge (Table 1). Moreover, ψ_i = 0.001, p_{II0} = 7 MPa and the time step of calculations Δt = 10 μs were taken for calculations.

Table 1. Characteristics of the propellant *II*

Heat of explosion	q_{sII} [MJ/kg]	4.9
Force	f_{II} [MJ/kg]	1.1
Covolume	α_{II} [dm^3/kg]	1.2
Ratio of specific heats	k [-]	1.2
Density	δ_{II} [kg/m^3]	1600
Burning rate coefficient	β_{II} [m/Pa^n·s]	$0.9 \cdot 10^{-9}$
Burning rate index	n_{II}	1
Initial surface of grain	S_{1II} [mm^2]	4492
Initial volume of grain	Λ_{1II} [mm^3]	1290
Shape coefficients	χ_{1II} [-]	1.08
	λ_{1II} [-]	-0.074

Table 2. Results of the solution MPIB of the recoilless propellant system: case *I* – with connected propellant to the projectile; case *II* – with not moving propellant

		case *I*	case *II*
Maximum pressure of gases inside the barrel	p_{maxII} [MPa]	84.8	74.0
Muzzle pressure of gases inside the barrel	p_{mII} [MPa]	67.6	60.1
Time to the projectile exit	t_m [ms]	6.68	6.54
Muzzle velocity of the projectile	V_m [m/s]	423.2	412.8
Fraction of propellant, which flew out of the barrel through the nozzle	η_d [-]	0.503	0.439

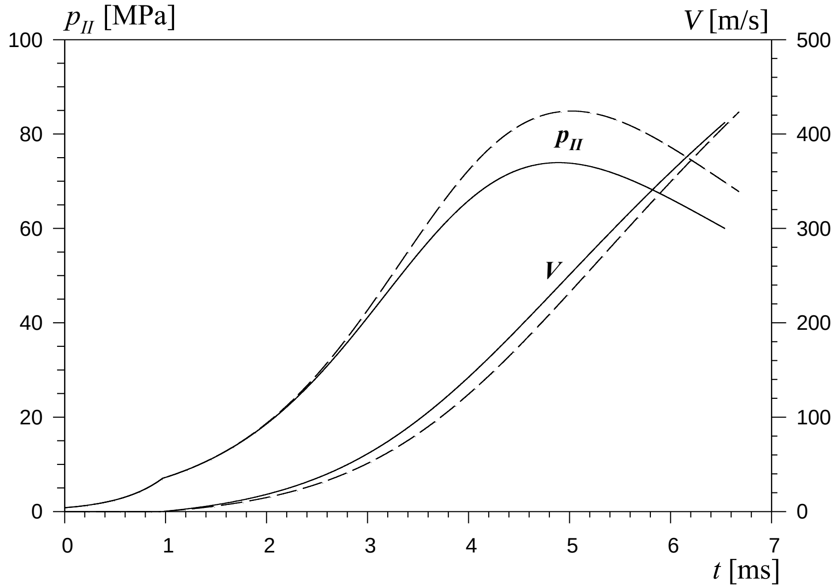

Fig. 5. The pressure p_{II} inside the barrel and projectile velocity V vs. the time t: case I – dashed line, case II – solid line

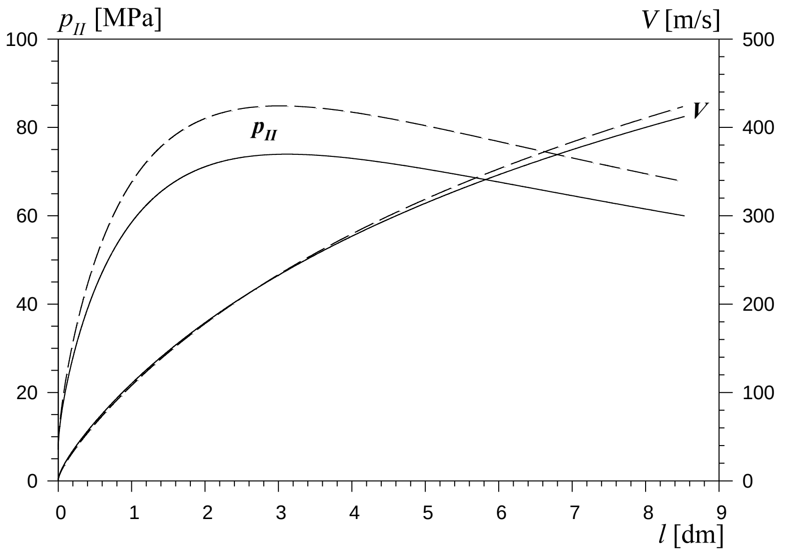

Fig. 6. The pressure p_{II} inside the barrel and the projectile velocity V vs. the projectile travel l: case I – dashed line, case II – solid line

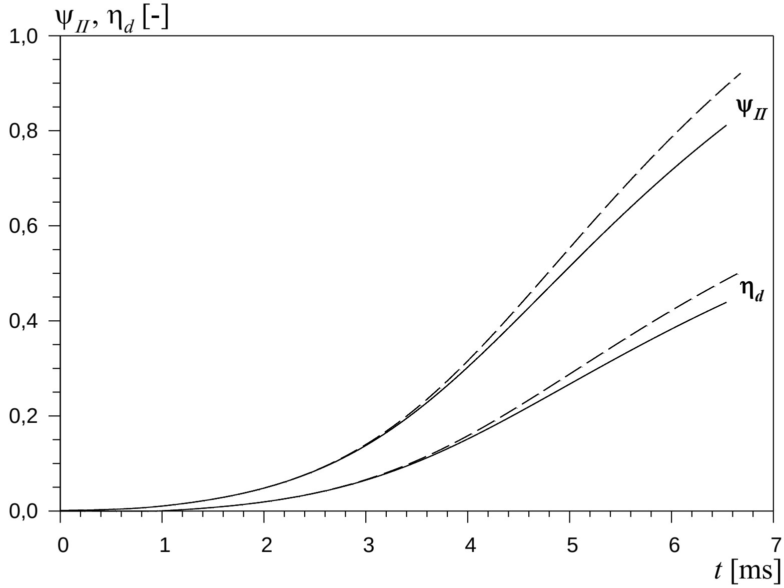

Fig. 7. Relative amount of the burned propellant ψ_{II} and the fraction of propellant η_d, which flew out of the barrel vs. time *t*: case *I* – dashed line, case *II* – solid line

5. CONCLUSIONS

The paper presents an extended general thermodynamic model of gun propellant systems considering additionally to the earlier considered systems: classical, two-chamber, and mortar one, the specificity of a recoilless system. The presented set of equations and, elaborated for its solution, a computer program allows us for calculation of the characteristics of work of the considered systems, especially the pressure of powder gases and the projectile velocity inside a barrel. The computer program can be used for investigation of influence of the changes in particular design characteristics of weapon as well as properties of a propellant charge on the parameters of propellant system operation.

The shot process in the considered recoilless system was divided into two characteristic periods (pyrostatic and pyrodynamic) separated by the moment of start of the projectile movement in a barrel bore. Simultaneously, at the same moment, due to fulfilment of the condition of recoilless character of the system operation, outflow of gasses through the nozzle (or nozzles set) begins. Numerical simulations were carried out for two variants of arrangement of propellant charge, i.e., with propellant charge moving together with a projectile and with propellant charge burning in a cartridge chamber. The obtained calculation results showed that the system in which propellant charge moves together with a projectile, has the maximum pressure higher of dozen or so percent in comparison with the system with propellant charge burning in a cartridge chamber and the muzzle velocity higher of several percent. Influence of a way of placement of propellant charge is the stronger, the higher is the ratio of its mass to the projectile mass.

Moreover, the elaborated program allows for investigation of the cases in which one of the phenomena, i.e., projectile movement or gases outflow through the nozzle starts earlier. In such a case, an undesirable phenomenon, i.e., gun recoil appears.

Because of outflow of propellant gases from the behind-projectile space, efficiency of the system decreases. In the considered case, up to the moment of the projectile exit, the powder gases flow out having the mass up to 50% of the mass of propellant charge (Table 2). Thus, the efficiency of a recoilless system is only a few percent and it is significantly lower than the efficiency of propellant systems with the closed barrel inlet.

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Układ bezodrzutowy jako szczególna postać uogólnionego modelu balistyki wewnętrznej lufowych układów miotających

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Streszczenie. W artykule zaprezentowano rozwinięcie uogólnionego modelu termodynamicznego balistyki wewnętrznej lufowych układów miotających, polegające na uwzględnieniu specyfiki bezodrzutowego układu miotającego. Przedstawiony model fizyczny i matematyczny umożliwiają symulacje pracy klasycznego układu miotającego oraz układów nieklasycznych: dwukomorowego, moździerzowego oraz rozpatrywanego w pracy układu bezodrzutowego. W celu przeprowadzenia symulacji działania układu bezodrzutowego, opracowano program komputerowy numerycznego rozwiązania układu równań uogólnionego modelu matematycznego. Obliczenia przeprowadzono dla dwóch konfiguracji konstrukcyjnych układu bezodrzutowego, różniących się sposobem rozmieszczenia ładunku miotającego, tj. z ładunkiem miotającym przemieszczającym się wraz z pociskiem oraz z ładunkiem miotającym spalającym się w komorze nabojowej. Otrzymane wyniki obliczeń pokazują, że układ w którym ładunek miotający przemieszcza się razem z pociskiem cechuje się wyższym ciśnieniem maksymalnym gazów oraz wyższą prędkością wylotową pocisku, w porównaniu do układu z ładunkiem miotającym spalającym się w komorze nabojowej. Wpływ sposobu umieszczenia ładunku miotającego jest tym silniejszy, im większy będzie stosunek jego masy do masy pocisku. Otrzymane wyniki symulacji, a w szczególności ciśnienie gazów prochowych i prędkość pocisku w przewodzie lufy, stanowią podstawowe informacje, wykorzystywane w procesie projektowania i optymalizacji konstrukcji układów bezodrzutowych broni palnej.
Słowa kluczowe: mechanika, balistyka wewnętrzna, bezodrzutowy układ miotający