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Ballistic Model of Two-Stage Light Gas Gun

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Abstract. A physical model and specificity of a two-stage light gas gun propulsion system are presented in this paper. For the considered system, a mathematical model of phenomena inside a combustion chamber, a light gas filled chamber, and a barrel was worked out. A numerical solution of the proposed model for the considered propulsion system gives pressures of powder gases, pressure of light gas, and motion parameters of a piston and a projectile. On the basis of the results of the accomplished calculations, influence of system structural parameters on the maximum pressure inside a compression chamber and a muzzle velocity of a projectile has been analysed. The final results of this work were used for development of the first in Poland a laboratory station with two-stage light gas gun intended for experimental investigation in the field of terminal ballistics of objects moving at hypersonic velocities.
Keywords: light gas gun, propulsion system, hypervelocity, interior ballistics

SYMBOLS

a	m/s	–	speed of sound in air
c_{v1}	J/(kg·K)	–	specific heat at constant volume of propellant gases
c_{v2}	J/(kg·K)	–	specific heat at constant volume of light gas
E_p	J	–	energy loss due to air resistance
E_1	J	–	kinetic energy of piston
E_2	J	–	kinetic energy of projectile
f	J/kg	–	„force"
k_p	-	–	ratio of specific heats of air
k_1	-	–	ratio of specific heats of propellant gases
k_2	-	–	ratio of specific heats of light gas
l	m	–	projectile travel inside barrel
l_w	m	–	total projectile travel inside barrel
l_1	m	–	length of pump tube
L	m	–	piston travel
m_i	kg	–	mass of light gas
m	kg	–	mass of projectile
M	kg	–	mass of piston
p_i	Pa	–	initial pressure of light gas
p_f	Pa	–	shot start pressure
p_p	Pa	–	pressure of air ahead of projectile
p_1	Pa	–	pressure of propellant gases
p_2	Pa	–	pressure of light gas
Q_s	J	–	energy from combustion of propellant
R_1	J/(kg·K)	–	specific propellant gases constant
R_2	J/(kg·K)	–	specific light gas constant
s_1	m^2	–	cross-section area of pump tube
s_2	m^2	–	cross-section area of barrel
S_1	m^2	–	initial surface of grain of propellant
t	s	–	time
T_i	K	–	initial temperature of light gas
T_s	K	–	isochoric flame temperature of propellant
T_0	K	–	reference temperature
T_1	K	–	temperature of propellant gases
T_2	K	–	temperature of light gas
u_1	m/(s·Pa)	–	burning rate coefficient of propellant
U_i	J	–	initial energy of light gas
U_1	J	–	internal energy of propellant gases
U_2	J	–	internal energy of light gas
v	m/s	–	projectile velocity
V	m/s	–	piston velocity
W_i	m^3	–	initial volume of pump tube

W_0	m^3	–	initial volume of combustion chamber
W_1	m^3	–	volume behind piston
W_2	m^3	–	current volume of pump tube (space behind projectile)
α	m^3/kg	–	propellant gases covolume
δ	kg/m^3	–	density of propellant
κ_1, λ_1	-	–	shape coefficients of propellant grain
Λ_1	m^3	–	initial volume of grain of propellant
φ	-	–	coefficient of secondary works
ψ	-	–	relative amount of burned propellant
ψ_z	-	–	relative amount of burned propellant at ignition time
ω	kg	–	mass of propellant charge

1. INTRODUCTION

A classical propellant propulsion system, commonly used in weapon [1, 2], in which the source of energy is a propellant charge, is able to propel the projectile up to a velocity of approx. 1800 m/s, i.e., to hypersonic speed. Research on increasing the muzzle velocity of the projectile led to the development of, inter alia, the following systems [3-6]:

- Travelling Charge System – TCS,
- Serial Chamber Gun System – SCS,
- ElectroThermal gun system – ET,
- ElectroThermal-Chemical gun system – ETC,
- Electromagnetic gun (railgun, coilgun),
- RAM accelerators.

Another way to propel the projectile to the velocities higher than in classical propulsion systems is a two-stage system [7, 8], in which the projectile is powered by compressed light gas. The two-stage light gas gun can propel a projectile to a velocity of several km/s, i.e., to hypersonic speeds. For this reason, this system can be used for investigations on the phenomena of external and terminal ballistics, including those accompanying collisions at high velocities, or research on the dynamic properties of construction materials, i.e., both in military and civilian areas.

Therefore, at the Institute of Armament Technology (IAT) of the Faculty of Mechatronics, Armaments and Aerospace of the Military University of Technology (Warsaw, Poland), the idea of designing and fabricating the first in Poland a laboratory station with two-stage light gas gun system was born, intended for the implementation of experimental tests in the field of terminal ballistics of various types of projectiles/objects (e.g. small calibre projectiles, fragments, etc.) moving at hypersonic velocities, i.e., above 5 Ma. Research works on the construction of the above-mentioned system was undertaken at the IAT in 2020 as a part of the university research project No. 777 “Construction and testing of a laboratory test station with a hypersonic propulsion system - Part I”. As a result of the project, the concept of a two-stage system that uses light gas (helium) expansion energy to propel projectiles/objects was proposed.

One of the stages of developing the concept of the system is selection of the so-called loading conditions ensuring achievement of the assumed muzzle velocity (kinetic energy) of the projectile at an acceptable pressure of gases. In order to determine the loading conditions, a physical model of a two-stage light gas gun system and a mathematical model of the shooting phenomenon were developed. As a result of solving the equations of the mathematical model, numerical tests were carried out on the influence of selected parameters of the two-stage system on its shot characteristics, including the projectile muzzle velocity and the maximum pressure of powder gases in a combustion chamber and light gas in a compression chamber (space behind the projectile).

2. PHYSICAL MODEL

The considered here two-stage light gas gun is presented in Fig. 1.

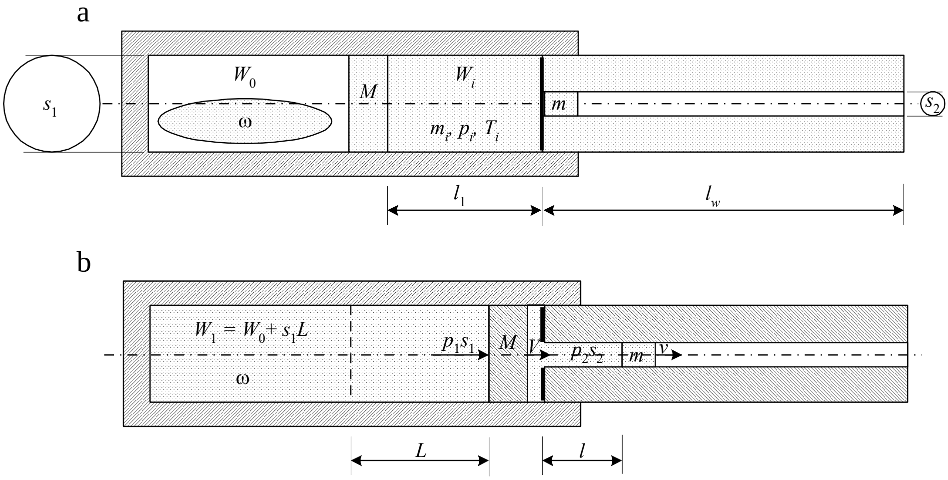

Fig. 1. Schematic of two-stage light-gas gun system: a – before shot, b – during shot

The set of phenomena from the moment of the initiation of combustion of the propellant charge ω to the exit of the projectile m from the barrel, i.e., travelling the distance $l = l_w$, will be considered. The presented schematic shows that the two-stage gun is a system of two spaces: a propellant combustion chamber with the initial volume W_0 and a pump tube (compression chamber) with the initial volume W_i filled with light gas of the mass m_i, the pressure p_i, and the temperature T_i.

These spaces (stages of the system) are separated by the piston *M*. As a result of initiating the combustion of the propellant charge, propellant gases are formed which drive the piston. Then, the moving piston compresses the light gas located in the compression chamber (compression space). A petal-valve diaphragm retains the light gas until pressure reaches the shot start pressure p_f (so-called forcing pressure). When the pressure p_f is reached, the diaphragm bursts and the projectile is accelerated by the rapidly expanding the light gas down the barrel bore. In the system under consideration, the pressure at which the projectile starts to move is about ten times higher than the forcing pressure in a classical propulsion system [9].

Due to the specificity of operation of the considered system, during the shot in a two-stage system, we can distinguish 3 characteristic periods:

– the first lasting from the moment of ignition of the propellant charge until the start moving of the piston;
– the second one from the moment of starting the piston to the moment of starting the projectile, i.e., reaching the start pressure (forcing pressure) by the compressed light gas;
– the third one from the moment of the start moving the projectile to the moment of its exit from the barrel.

3. MATHEMATICAL MODEL OF THE TWO-STAGE SYSTEM WORKING

The mathematical model was developed to describe the phenomena that take place in the combustion chamber (behind the piston), in the pump tube (the compression chamber), and in the barrel (in the space behind the projectile). These phenomena comprise the combustion of the propellant charge, the compression of the light gas as well as motion of the piston along the pump tube and motion of the projectile along the barrel bore.

The following major assumptions were used in formulating the equations of the mathematical model:

– ignition and combustion of the propellant charge proceed according to the geometric model [2],
– the thermodynamic characteristics of the propellant gases and light gas (e.g. specific heat ratio and gas constant) are constant throughout the process,
– the considered thermodynamic processes are adiabatic ones.

The governing equation of the mathematical model is the energy balance based on the first law of thermodynamics

$$Q_s + U_i = U_1 + U_2 + E_1 + E_2 + E_p \tag{1}$$

considering that:

$$Q_s = c_{v1}(T_s - T_0)\omega\psi$$
$$U_i = c_{v2}(T_i - T_0)m_i$$
$$U_1 = c_{v1}(T_1 - T_0)\omega\psi$$
$$U_2 = c_{v2}(T_2 - T_0)m_i$$

$$E_1 = \varphi M \frac{V^2}{2},\quad E_2 = m\frac{v^2}{2},\quad E_p = s_2\int_0^l p_p dl$$

we obtain the energy balance in the form:

$$\frac{f}{k_1 - 1}\omega\psi - \frac{R_1 T_1}{k_1 - 1}\omega\psi = \varphi M\frac{V^2}{2} + m\frac{v^2}{2} + \frac{R_2 T_2}{k_2 - 1}m_i - \frac{R_2 T_i}{k_2 - 1}m_i + E_p \tag{1a}$$

where $f = R_1 T_s$.

Taking into consideration the equations of state of:

– propellant gases

$$R_1 T_1 \omega\psi = p_1 W_1 = p_1\left(W_0 + s_1 L - \frac{\omega}{\delta}(1-\psi) - \alpha\omega\psi\right) \tag{2}$$

– light gas (during compression)

$$R_2 T_2 m_i = p_2 W_2 = p_2(s_1 l_1 - s_1 L + s_2 l) \tag{3}$$

– light gas at the initial time

$$R_2 T_i m_i = p_i s_1 l_1 \tag{4}$$

and the light gas adiabatic equation

$$p_2 = p_i\left(\frac{s_1 l_1}{s_1 l_1 - s_1 L + s_2 l}\right)^{k_2} \tag{5}$$

we have the energy balance (1a) in the form:

$$p_1 = \frac{f\omega\psi - (k_1 - 1)\left(\varphi M\frac{V^2}{2} + m\frac{v^2}{2} + E_p\right) - \frac{k_1 - 1}{k_2 - 1}p_i s_1 l_1\left[\left(\frac{l_1}{l_1 - L + \frac{s_2}{s_1}l}\right)^{k_2 - 1} - 1\right]}{\left(W_0 + s_1 L - \frac{\omega}{\delta}(1-\psi) - \alpha\omega\psi\right)} \tag{1b}$$

Other relationships of the model are:

– equation of the piston motion

$$\frac{dV}{dt}=\frac{s_1\left(p_1-p_2\right)}{\varphi M} \tag{6}$$

where $\varphi=1+\frac{1}{3}\frac{\omega}{M}$

– definition of the piston velocity

$$\frac{dL}{dt}=V \tag{7}$$

– equation of the projectile motion

$$\frac{dv}{dt}=\frac{s_2\left(p_2-p_p\right)}{m} \tag{8}$$

– definition of the projectile velocity

$$\frac{dl}{dt}=v \tag{9}$$

– change in the relative burnt mass of the propellant charge

$$\frac{d\psi}{dt}=\frac{S_1}{\Lambda_1}\sqrt{1+4\frac{\lambda_1}{\kappa_1}\psi}\cdot u_1 p_1 \tag{10}$$

– pressure of air ahead of the projectile [10]

$$p_p=p_a\left[1+k_p M_a{}^2\left(\frac{1+k_p}{4}+\sqrt{\left(\frac{1+k_p}{4}\right)^2+M_a{}^{-2}}\right)\right], \tag{11}$$

where: $M_a = v/a$, a = 343.8 m/s, p_a = 101325 Pa, and k_p = 1.4.

The presented mathematical model of the shot is a closed system of equations (1-11), which after solving for the following initial conditions:

$$t=0,\ \psi=\psi_z,\ p_1(\psi_z),\ p_2=p_i,\ l=L=0,\ v=V=0$$

provides the information about the pressures in the combustion chamber and the compression chamber (in the space behind the projectile) as well as about the parameters of the piston and projectile motion.

4. INVESTIGATIONS OF THE SPECIFICITY OF THE TWO-STAGE SYSTEM

The research on the specificity of the operation of the considered system was carried out in two stages.

In the first stage, by means of successive simulations, the parameters of the tested system were determined in the form of design characteristics as well as the energy-ballistic and geometric properties of the propellant charge, presented in Table 1.

Table 1. Input data used in the numerical simulations

Mass of the propellant charge	ω, kg	0.30
Initial volume of the combustion chamber	W_0, m^3	373×10^{-6}
Mass of the piston	M, kg	0.4
Mass of the projectile	m, kg	0.010
Cross-section area of the pump tube in the diameter D = 38.0 mm	s_1, m^2	1134×10^{-6}
Cross-section area of the barrel in the diameter d = 12.7 mm	s_2, m^2	126.7×10^{-6}
Length of the pump tube	l_1, m	2.81
Total projectile travel inside the barrel	l_w, m	2.5
Initial pressure of light gas	p_i, MPa	20
„Force” of propellant	f, J/kg	0.9×10^6
Propellant gases covolume	α, m^3/kg	1.49×10^{-3}
Ratio of specific heats of propellant gases	k_1	1.2
Ratio of specific heats of light gas (helium)	k_2	1.67
Density of propellant	δ, kg/m^3	1600
Burning rate coefficient of propellant	u_1, m/(s·Pa)	0.56×10^{-9}
Initial surface of grain of propellant	S_1, m^2	51.1×10^{-6}
Initial volume of grain of propellant	Λ_1, m^3	17.2×10^{-9}
Shape coefficients of the propellant grain	χ_1	0.7774
	λ_1	0.1244

In these simulations, it was assumed that the propellant charge, based on single-base propellant, would be placed in the case of the 35 × 228 mm artillery round. The use of the case with an igniter will allow us to ignite the propellant and to seal the combustion chamber. In addition, it was assumed that the barrel of the two-stage system will be of the smooth bore, calibre 12.7 mm with the length of 2.5 m.

In the second stage, the influence of selected parameters of the system on its work characteristics, in particular on the parameters in the barrel, was analysed.

Simulations carried out taking into account the following conditions:

– the movement of the piston begins when $p_1 > p_i$,
– the movement of the projectile begins when $p_2 > p_f$,
– the velocity of the piston at the end of propulsion (at the moment of projectile exit) is equal to zero.

Moreover, $\psi_z = 0.001$, $p_f = 200$ MPa, and the time step $\Delta t = 5$ μs were taken for calculations.

As a result of solving the presented system of equations, one obtains, gas pressure in the combustion chamber and in the compression chamber, and the parameters of the piston and projectile motion (Fig. 2-6). The main simulation results are presented in Table 2.

Table 2. The main parameters of the shot

Total time of the shot, ms	5.31
Time of projectile movement in the barrel, ms	0.87
Maximum pressure in the combustion chamber, MPa	387
Maximum pressure of light gas, MPa	1048
Maximum velocity of the piston, m/s	1197
Muzzle velocity of the projectile, m/s	6988

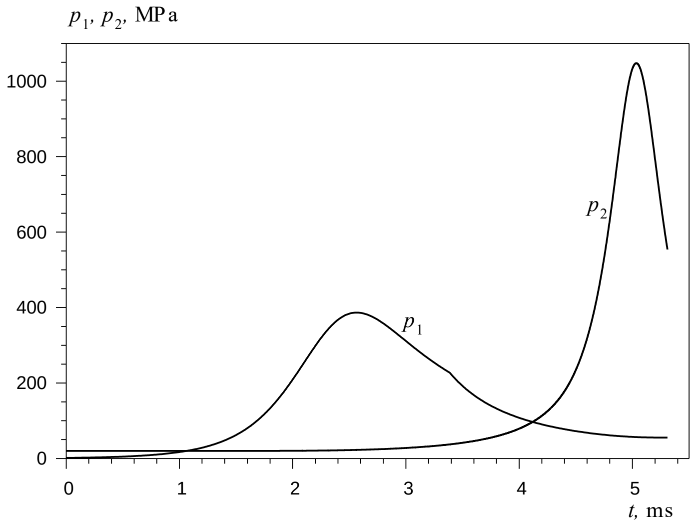

Fig. 2. The pressure p_1 inside the combustion chamber and p_2 inside the pump tube vs. time

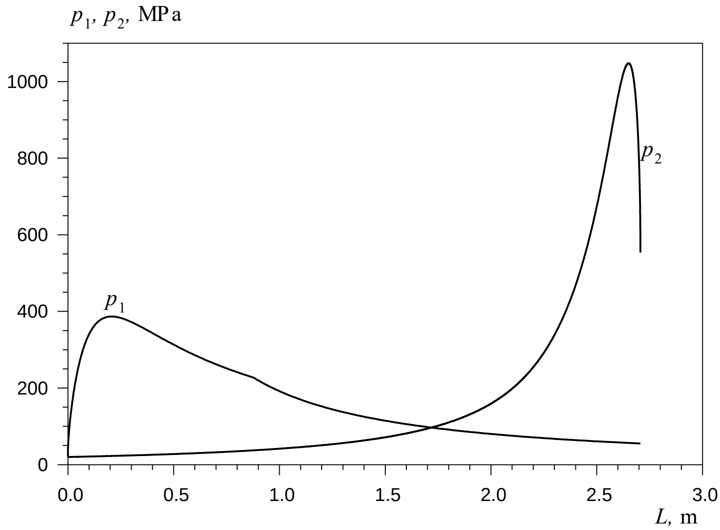

Fig. 3. The pressure p_1 inside the combustion chamber and p_2 inside the pump tube vs. the piston travel L

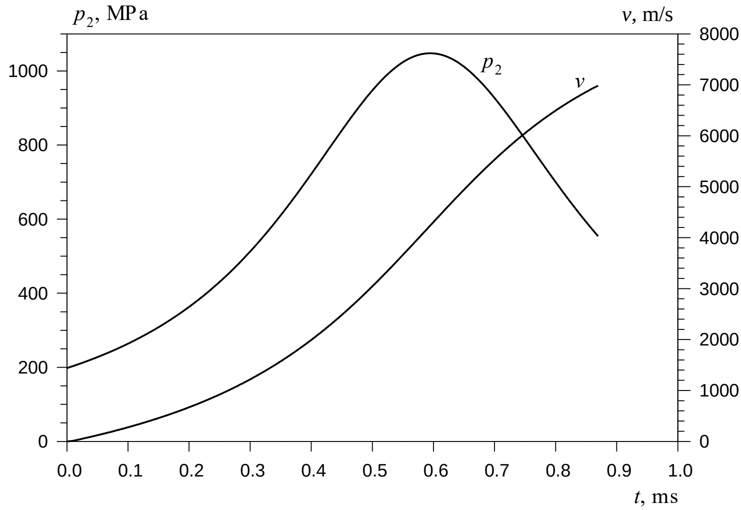

Fig. 4. The pressure p_2 inside the pump tube and the projectile velocity v vs. the time t

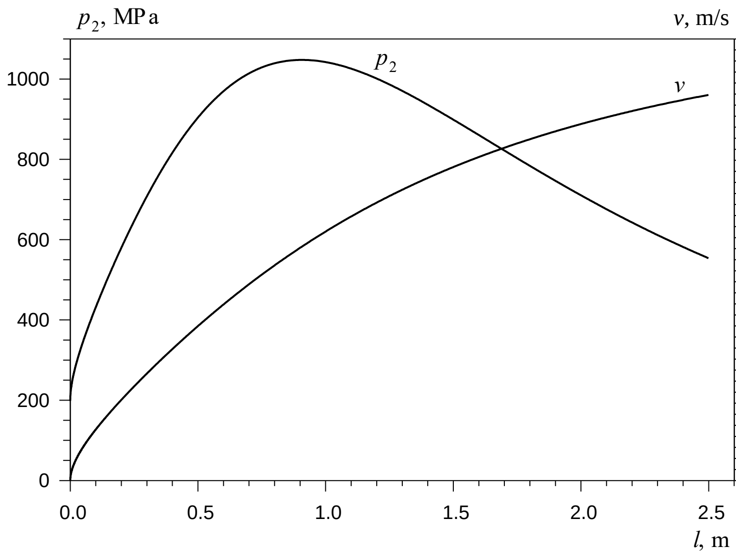

Fig. 5. The pressure p_2 inside the pump tube and the projectile velocity v vs. the projectile travel l

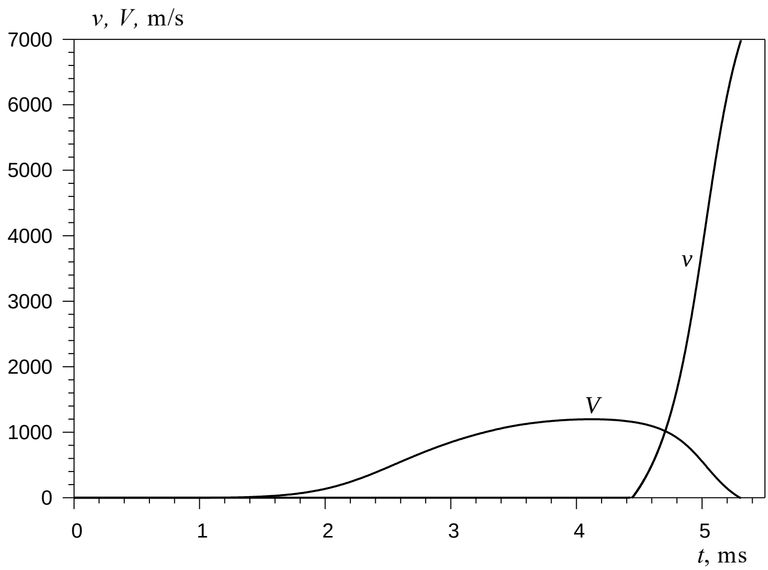

Fig. 6. The piston velocity V and the projectile velocity v vs. the time t

Using the developed computer program, the influence of system parameters, such as:

- mass of the projectile, m,
- mass of the piston, M,
- shot start pressure, p_f,
- cross-section area of the pump tube (the compression chamber), s_1,
- initial volume of the pump tube (the compression chamber), W_i,
- initial pressure of light gas, p_i,

on the maximum pressure p_{2m} and the muzzle velocity v_w of the projectile.

The results of calculations were presented in the form of graphs (Figs. 7-10) of relative percentage changes in δp_{2m} and δv_w as a function of relative changes in δm, δM, δp_f, δs_1, δW_i, and δp_i. The system structural parameters from Table 1 and the corresponding values of the shot characteristics presented in Table 2 were adopted as a reference (a base).

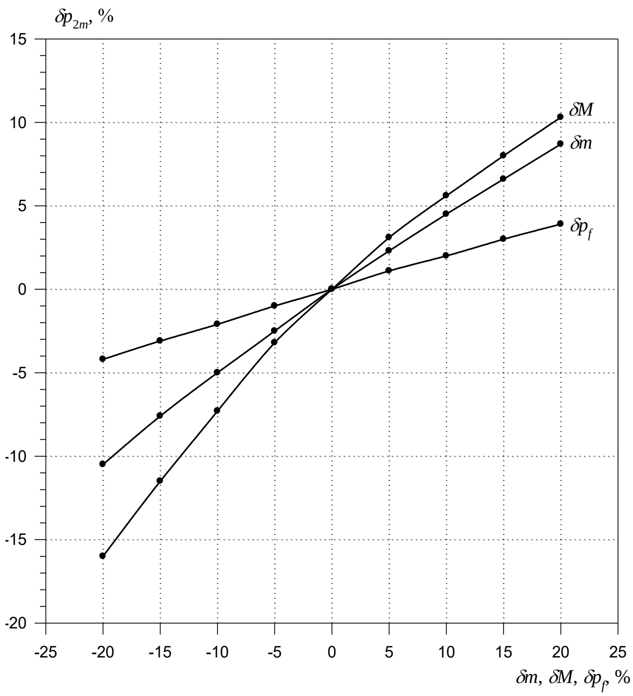

Fig. 7. Relative changes of the maximum pressure p_{2m} vs. the relative changes m, M, p_f

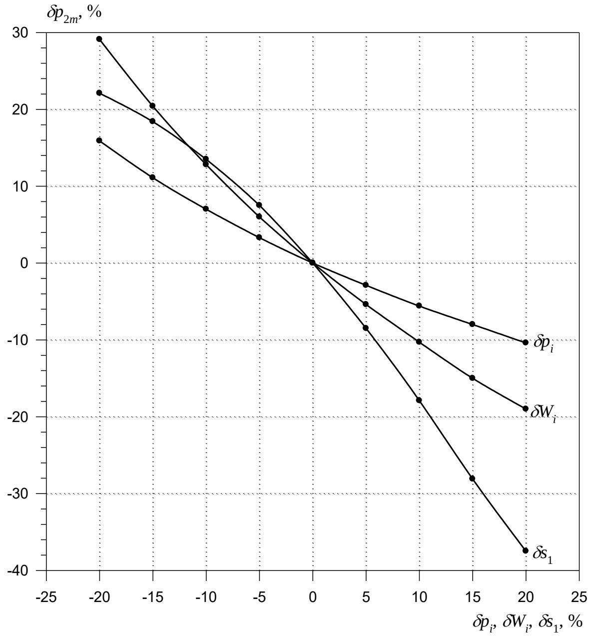

Fig. 8. Relative changes of the maximum pressure p_{2m} vs. the relative changes s_1, W_i, p_i

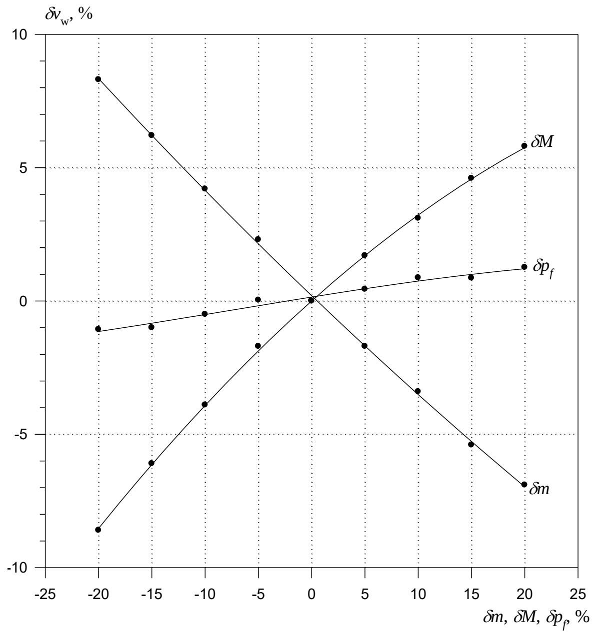

Fig. 9. Relative changes of the projectile muzzle velocity v_w vs. the relative changes m, M, p_f

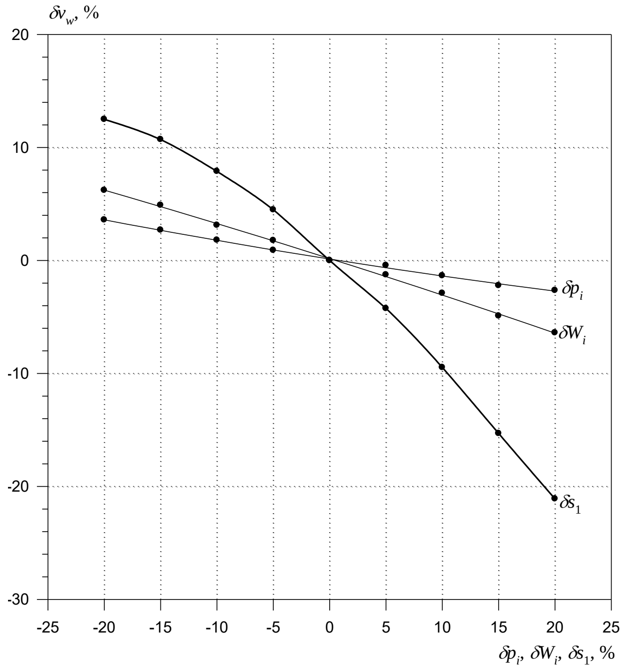

Fig. 10. Relative changes of the projectile muzzle velocity v_w vs. the relative changes s_1, W_i, p_i

5. CONCLUSIONS

The presented mathematical model of the shot phenomenon in the two-stage gun system and the computer code enable us simulation of operation of the system and study of its specificity. The results of simulations are used for the analysis and design of such systems.

The investigation of influence of the system structural parameters on the maximum pressure inside the compression chamber and the muzzle velocity of the projectile allow us to formulate the following conclusions:

a) the initial volume W_i and the cross-section area s_1 of the pump tube (the compression chamber) have the greatest influence on the pressure p_2 of the light gas in the compression chamber; the projectile mass m, the piston mass M, and the initial pressure p_i of light gas have a smaller (over a dozen percent) effect; the forcing pressure p_f has little influence (p_{2m} changes approx. 4%);

b) among the tested parameters, the cross-section area s_1 of the pump tube (compression chamber) has the greatest impact on the muzzle velocity v_w of the projectile; the other parameters cause a few percent changes in the muzzle velocity; the forcing pressure p_f has the smallest, practically negligible effect (v_w changes approx. 1%);

c) the changes (derivative) of the projectile velocity *v* vs. travel (Fig. 5) indicates the possibility of increasing the muzzle velocity by extending the barrel length.

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Model balistyczny dwustopniowego układu miotającego

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Streszczenie. W pracy przedstawiono model fizyczny ilustrujący specyfikę działania dwustopniowego układu miotającego. Dla rozpatrywanego układu sformułowano termodynamiczny model matematyczny zjawisk zachodzących w komorze spalania prochowego ładunku miotającego oraz w komorze sprężania i lufie. W wyniku numerycznego rozwiązania zaproponowanych równań otrzymuje się m.in. ciśnienie gazów prochowych w komorze spalania, ciśnienie gazu lekkiego w komorze sprężania oraz lufie, jak również charakterystyki ruchu tłoka i pocisku dla przyjętego układu konstrukcyjnego. Na podstawie wykonanych obliczeń przeanalizowano wpływ parametrów konstrukcyjnych układu na charakterystyki jego pracy, m.in. napęd pocisku. Wyniki pracy zostały wykorzystane do opracowania pierwszego w Polsce stanowiska badawczego, przeznaczonego do realizacji badań doświadczalnych z zakresu balistyki końcowej obiektów poruszających się z prędkościami hiperdźwiękowymi.

Słowa kluczowe: działo gazowe, układ miotający, prędkość hiperdźwiękowa, balistyka wewnętrzna