Proceedings of International Scientific Conference "Defense Technologies" **DefTech 2021**,
Faculty of Artillery, Air Defense and Communication and Information Systems

FORMULATION OF INTERIOR BALLISTIC MODEL OF GAS DELAYED BLOWBACK OPERATION FIREARM

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Abstract: *The paper presents interior ballistic model of gas delayed blowback operation firearm. The mathematical equations and relations describing the working of such weapon automatic are presented. Furthermore, sample theoretical results of numerical calculations aimed at check of influence of dimension and position of gas port on braking the recoil assembly movement are shown. To achieve this goal, numerical methods and computer simulations were used. The next step is to detailed verification and validation the correctness of the proposed model by comparing the theoretical results with the results of experimental tests carried out on a newly constructed laboratory stand.*

Keywords: *mechanical engineering, internal ballistics, small arms, firearm, delayed blowback*

Nomenclature:

c_p	- specific heat capacity at constant pressure	[J/(kg·K)]
c_v	- specific heat capacity at constant volume	[J/(kg·K)]
d_{gp}	- gas port diameter	[mm]
d_{gpi}	- gas piston diameter	[mm]
E_k	- projectile kinetic energy	[J]
E_s	- recoiling assembly (slide and piston) energy	[J]
E_{sp}	- recoil spring energy	[J]
f	- propellant force	[MJ/kg]
F_r	- projectile resistance force	[N]
I	- summary enthalpy of gas	[J]
I_g	- enthalpy of gas flowing out of the barrel bore into the gas chamber or flowing out of the gas chamber into the barrel bore	[J]
I_m	- enthalpy of gas flowing out of the barrel bore through the muzzle	[J]
I_p	- projectile moment of inertia	kg·m^2
k	- ratio of specific heats	[-]
k_{sp}	- recoil spring constant	[N/m]
l	- projectile travel	[m]
l_g	- projectile travel to gas port (gas port location)	[m]
l_m	- overall projectile travel inside the barrel	[m]
L	- recoiling assembly travel	[m]
m	- projectile weight	[g]
M	- recoiling assembly weight	[g]
Q	- energy from combustion of the propellant	[J]
q_s	- heat of combustion of the propellant	[MJ/kg]
p	- gas pressure in the barrel bore	[MPa]
p_0	- ambient pressure	[MPa]
p_{gch}	- gas pressure in the gas chamber	[MPa]

R	- universal gas constant	[J/(K·mol)]
s	- barrel bore cross-sectional surface area	[mm^2]
s_{gch}	- gas chamber cross-sectional surface area	[mm^2]
s_{gp}	- gas port cross-sectional surface area	[mm^2]
T	- gas temperature in the barrel bore	[K]
T_0	- initial temperature	[K]
T_1	- temperature of propellant combustion	[K]
T_{gch}	- gas temperature in the gas chamber	[K]
t	- time	[s]
U	- internal energy of propellant gas in barrel bore	[J]
U_{gch}	- internal energy of propellant gas in gas chamber	[J]
v	- projectile velocity	[m/s]
W	- recoiling assembly velocity	[m/s]
W_0	- initial volume of cartridge chamber	[$cm^{3]}$
W_{0gch}	- initial volume of gas chamber	[cm^3]
W_p	- projectile work	[J]
W_r	- projectile resistance work	[J]
W_s	- recoiling assembly work	[J]
x_0	- recoil spring pre-deflection	[m]
α	- propellant gas co-volume	[dm^3/kg]
α_g	- exponent in the burning law	[-]
γ	- relative mass (volume) of the propellant gas which flow out of the barrel bore through the muzzle	[-]
Γ	- dynamic vivacity	[$(MPa \cdot s)^{-1}$]
δ	- propellant density	[kg/m^3]
η	- relative mass (volume) of the propellant gas which flow out of the barrel bore to the gas chamber	[-]
η_b	- rifling twist	[m]
θ	- function of ratio of specific heats (θ=k-1)	[-]
ξ_g	- coefficient of gas flow loss from the barrel to the gas chamber	[-]
ξ_m	- coefficient of gas outflow loss from the barrel to the ambient	[-]
ρ	- barrel bore gas propellant density	[kg/m^3]
ρ_{gch}	- gas chamber gas propellant density	[kg/m^3]
Ψ	- relative burnt mass (volume) of the propellant	[-]
ω	- propellant weight	[g]

1. Introduction

The permanent development of technology and changes on the battlefield influence on modernization of small arms. One of the operation systems in firearms is gas delayed blowback system [1]. It is some modification of the simple blowback operation, with the difference that there is additional components which cause decelerating the recoil assembly. In this solution, during the shot, some part of propellant gas is flow out of the barrel bore through gas port to the gas chamber and then press against gas piston which is connected with the slide. Thanks to it, this method provides some benefits, like for example: reducing of recoil as well as possibility of using ammunition with a higher muzzle energy.

Therefore, the modernization of this type of small arms seems to be a future-proof and we can suppose that the design of modern armament with this type operation system can be response to today's military needs.

In order to reduce the cost and duration of research during the development stage, apply numerical methods and computer simulations [2] is justified. Describing the phenomena occurring in firearm using suitable models physical and mathematical is required. The influence of some parameters of the weapon on the kinematic and ballistic characteristics is the key to appropriate adjustment and optimization construction.

Moreover, in the available literature there are no studies containing results which could be used in design of weapon using this system. Although, automatic firearm action was analyzed in some papers, f.e. [3,4,5], but it refers to other automatic systems. Thanks to this, the attempt to solve problem of gas delayed blowback operation firearm action is absolutely justify.

2. Interior Ballistic Model of Gas Delayed Blowback Operation Firearm

Interior ballistic model of a gas delayed blowback operation firearm is based on HK P7 9 mm pistol. It is primarily due to the fact this pistol is available to the author and can be examined and used for shooting tests by him. The mathematical model describes the action from the moment of ignition of the propellant until the pressure in gas chamber and in the barrel bore equals the ambient pressure. In order to formulate the equations, thermodynamic approach and theory of internal ballistics [6] were applied. Due to the preliminary quality of model, to solve this problem, some simplifying assumptions were accept.

For this system of weapon action, the equations are as follows:

a) <u>for the barrel bore:</u>

<u>the energy conservation equation:</u>

- for the gases flow out of the barrel bore to the gas chamber takes the form:

$$dU = dQ - dW_p - dW_s - dI \tag{1}$$

considering that:

$$dU = d\ c_v\omega\ \psi - \eta - \gamma\ T\ = c_v\omega\ T\ d\psi - d\eta - d\gamma\ +\ \psi - \eta - \gamma\ dT$$

$$\boldsymbol{dQ = d\ c_v\ T_1 - T_0\ \omega\psi\ = q_s\omega d\psi}$$

$$dW_s = dE_k + dW_r$$

$$\boldsymbol{dE_k = d\ \ \frac{4\pi^2 I_p}{\eta_b^2} + m + \frac{\omega}{3}\ \ v^2\ =\ \frac{4\pi^2 I_p}{\eta_b^2} + m + \frac{\omega}{3}\ \ vdv}$$

$$\boldsymbol{dW_r = F_r v}$$

$$dW_s = dE_s + dE_{sp}$$

$$\boldsymbol{dE_s = d\ \ \frac{MW^2}{2}\ \ = MWdW}$$

$$dE_{sp} = F_{sp}W = k_{sp}\ \ x_0 + L\ \ W$$

$$dI = dI_g + dI_m$$

$$\boldsymbol{dI_g = c_p\omega T d\eta}$$

$$dI_w = c_p \omega T d\gamma$$

we obtain the energy balance (changes of the propellant gases temperature) in the form:

$$\frac{dT}{dt} = \frac{q_s - c_v T \ \omega \frac{d\psi}{dt} - \theta c_v \omega T \frac{d\eta}{dt} - RT\omega \frac{d\gamma}{dt} - \frac{dW_p}{dt} - \frac{dW_s}{dt})}{c_v \omega(\psi - \eta - \gamma)} \tag{2}$$

- for the gases flow out of the gas chamber to the barrel bore takes the form:

$$dU = dQ - dW_p - dW_s - dI \tag{3}$$

considering that:

$$dU = d \ c_v \omega \ \psi - \eta - \gamma \ T \ = c_v \omega \ T \ d\psi - d\eta - d\gamma \ + \ \psi - \eta - \gamma \ dT$$

$$dQ = d \ c_v \ T_1 - T_0 \ \omega \psi \ = q_s \omega d\psi$$

$$dW_p = dE_k + dW_r$$

$$dE_k = d \quad \frac{4\pi^2 I_p}{\eta_b^2} + m + \frac{\omega}{3} \quad v^2 \ = \ \frac{4\pi^2 I_p}{\eta_b^2} + m + \frac{\omega}{3} \quad v dv$$

$$dW_r = F_r v$$

$$dW_s = dE_s + dE_{sp}$$

$$dE_s = d \ \frac{MW^2}{2} \ = MWdW$$

$$dE_{sp} = F_{sp} W = k_{sp} \ x_0 + L \ W$$

$$dI = -dI_g + dI_m$$

$$dI_g = -c_p \omega T_{gch} d\eta$$

$$dI_m = c_p \omega T d\gamma$$

we obtain the energy balance (changes of the propellant gases temperature) in the form:

$$\frac{dT}{dt} = \frac{q_s - c_v T \ \omega \frac{d\psi}{dt} + \ T - kT_{gch} \ c_v \omega \frac{d\eta}{dt} - RT\omega \frac{d\gamma}{dt} - \frac{dW_p}{dt} - \frac{dW_s}{dt})}{c_v \omega(\psi - \eta - \gamma)} \tag{4}$$

- equation of barrel bore propellant gases density:

$$\rho = \frac{\omega(\psi - \eta - \gamma)}{W_0 - \frac{\omega}{\delta} \ 1 - \psi \ + s(l + L)} \tag{5}$$

- equation of state of barrel bore propellant gases:

$$p = \frac{\rho RT}{1 - \propto \rho} \tag{6}$$

- mass of gas generated by propellant combustion / equation of relative burnt mass of propellant:

$$\frac{d\psi}{dt} = \Gamma \ \psi \ p_0 \left(\frac{p}{p_0}\right)^{\propto g} \tag{7}$$

- equation of relative mass (volume) of the propellant gas flowing out of the barrel bore into the gas chamber: $(p \geq p_{gch})$

if: $\frac{p_{gch}}{p} \leq \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}}$

$$\frac{d\eta}{dt} = \frac{\xi_g \, s_{gp}}{\omega} \left(\frac{2}{k+1}\right)^{\frac{1}{k-1}} \sqrt{\frac{2k}{k+1}} \cdot \frac{p}{\sqrt{RT}} \tag{8}$$

if: $\frac{p_{gch}}{p} > \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}}$

$$\frac{d\eta}{dt} = \frac{\xi_g \, s_{gp}}{\omega} \sqrt{\frac{2k}{k-1}\left[\left(\frac{p_{gch}}{p}\right)^{\frac{2}{k}} - \left(\frac{p_{gch}}{p}\right)^{\frac{k+1}{k}}\right]} \cdot \frac{p}{\sqrt{RT}} \tag{9}$$

- equation of relative mass (volume) of the propellant gas flowing out of the gas chamber into the barrel bore: $(p < p_{gch})$

if: $\frac{p}{p_{gch}} \leq \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}}$

$$\frac{d\eta}{dt} = -\frac{\xi_g \, s_{gp}}{\omega} \left(\frac{2}{k+1}\right)^{\frac{1}{k-1}} \sqrt{\frac{2k}{k+1}} \cdot \frac{p_{gch}}{\sqrt{RT_{gch}}} \tag{10}$$

if: $\frac{p}{p_{kg}} > \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}}$

$$\frac{d\eta}{dt} = -\frac{\xi_g s_{gp}}{\omega} \sqrt{\frac{2k}{k-1}\left[\left(\frac{p}{p_{gch}}\right)^{\frac{2}{k}} - \left(\frac{p}{p_{gch}}\right)^{\frac{k+1}{k}}\right]} \cdot \frac{p_{gch}}{\sqrt{RT_{gch}}} \tag{11}$$

- equation of relative mass (volume) of the propellant gas flowing out of the barrel bore through the muzzle:

$$\frac{d\gamma}{dt} = \frac{\xi_m s}{\omega} \left(\frac{2}{k+1}\right)^{\frac{1}{k-1}} \sqrt{\frac{2\,k}{k+1}} \cdot \frac{p}{\sqrt{RT}} \tag{12}$$

b) <u>for the gas chamber:</u>

<u>the energy conservation equation:</u>
- for the gases flow out of the barrel bore to the gas chamber takes the form:

$$dU_{gch} = dI_g - dW_s \tag{13}$$

considering that:

$$dU_{gch} = d\left(c_v \omega \eta T_{gch}\right) = c_v \omega\left(T_{gch} d\eta + \eta dT_{gch}\right)$$

$$\boldsymbol{dI_g = c_p \omega T d\eta}$$

$$dW_s = dE_s + dE_{sp}$$

$$\boldsymbol{dE_s = d\left(\frac{MW^2}{2}\right) = MWdW}$$

$$dE_{sp} = F_{sp} W = k_{sp}\left(x_0 + L\right) W$$

we obtain the energy balance (changes of the propellant gases temperature) in the form:

$$\frac{dT_{gch}}{dt} = \frac{\left(kT - T_{gch}\right) c_v \omega \frac{d\eta}{dt} - \frac{dW_s}{dt}}{c_v \omega \eta} \tag{14}$$

- for the gases flow out of from the gas chamber to the barrel bore takes the form:

$$dU_{gch} = -dI_g - dW_s \tag{15}$$

considering that:

$$dU_{gch} = d\left(c_v \omega \eta T_{gch}\right) = c_v \omega\left(T_{gch} d\eta + \eta dT_{gch}\right)$$

$$\boldsymbol{dI_g = -c_p \omega T_{gch} d\eta}$$

$$dW_s = dE_s + dE_{sp}$$

$$\boldsymbol{dE_s = d\left(\frac{MW^2}{2}\right) = MWdW}$$

$$dE_{sp} = F_{sp} W = k_{sp}\left(x_0 + L\right) W$$

we obtain the energy balance (changes of the propellant gases temperature) in the form:

$$\frac{dT_{gch}}{dt} = \frac{\theta c_v(\omega\, T_{gch} \frac{d\eta}{dt} - \frac{dW_s}{dt})}{c_v \omega \eta} \tag{16}$$

- equation of gas chamber propellant gases density:

$$\rho_{gch} = \frac{\omega \eta}{W_{0gch} - s_{gch} L} \tag{17}$$

- equation of state of gas chamber propellant gases:

$$p_{gch} = \frac{\rho_{gch} R T_{gch}}{1 - \propto \rho_{gch}} \tag{18}$$

c) <u>other equations:</u>

- **equation of the slide motion:**

$$\frac{dW}{dt} = \frac{ps - p_{gch}s_{gch} - k_{sp}\ \ x_0 + L}{M} \tag{19}$$

- **definition of the slide velocity:**

$$\frac{dL}{dt} = W \tag{20}$$

- **equation of the pressure acting on the bottom of the projectile:**

$$p_p = \frac{p + \frac{\omega}{3m}\frac{F_r}{s}}{1 + \frac{\omega}{3m}} \tag{21}$$

- **equation of the projectile motion:**

$$\frac{dv}{dt} = \frac{sp_p - F_r}{m} \tag{22}$$

- **definition of the projectile velocity:**

$$\frac{dl}{dt} = v \tag{23}$$

Specifications of the propellant and firearm applied to this model are summarized in the Tables 1 and 2.

Table 1.

Weapon and round specifications.

	Parameter	Value
1	Projectile weight m [g]	8.0
2	Initial volume of cartridge chamber W_0 [cm^3]	0.57
3	Overall projectile travel inside the barrel l_m [m]	0.093
4	Projectile travel to gas port (gas port location) l_g [m]	0.00642
5	Gas port diameter d_{gp} [mm]	1.4
6	Initial volume of gas chamber W_{0gch} [cm^3]	1.64
7	Gas piston diameter d_{gpi} [mm]	7
8	Recoiling assembly weight M [g]	289
9	Recoil spring constant k_{sp} [N/m]	900
10	Recoil spring pre-deflection x_0 [m]	0.0564
11	Coefficient of gas flow loss from the barrel to the gas chamber ξ_g	1
12	Coefficient of gas flow loss from the barrel to the ambient ξ_m	1

Table 2.

Propellant charge specifications.

	Parameter	Value
1	Propellant weight ω [g]	0.34
2	Heat of propellant combustion q_s [MJ/kg]	4.06
3	Propellant force f [MJ/kg]	1.032
4	Propellant gas co-volume α [dm^3/kg]	1.18
5	Ratio of specific heats k	1.2541
6	Propellant density δ [kg/$m^{3]}$	1330
7	Universal gas constant R [J/(K·mol)]	360

Using the above data, simulations were carried out. Furthermore, to the model some interesting results obtained or estimated in [3] were used. It was:

- the interaction between projectile and barrel bore (in dynamic conditions of projectile movement),
- geometric burning law and dynamic vivacity.

The most significant achieved data was presented below. The Figure 1 shows the curves of pressure in barrel bore and gas chamber, while the Figure 2 show the changes velocity of projectile and slide.

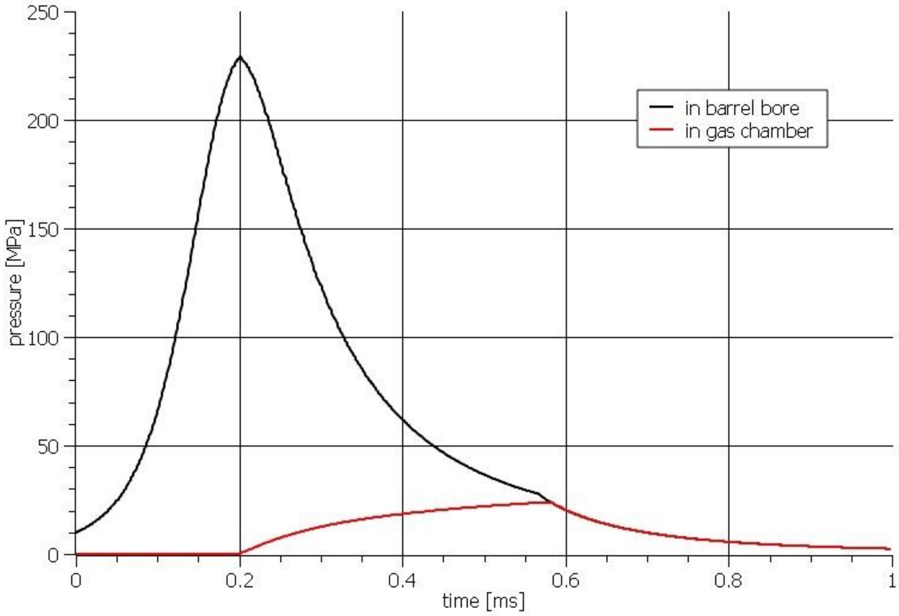

Figure 1. *Barrel bore pressure and gas chamber pressure as a function of time*

a) b)

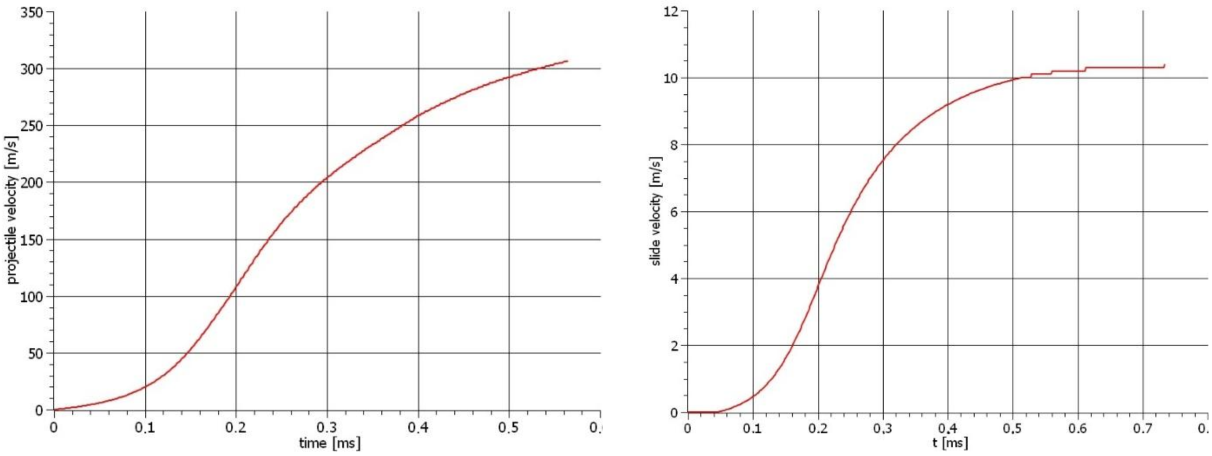

Figure 2. *Projectile velocity (a) and slide velocity (b) as a function of time*

Maximum barrel bore pressure was compared with obtained in [3] and this value can be considered to be correct. The course of gas chamber pressure is also in line with expectations.

The calculated maximum projectile velocity is 306 m/s. Taking into account the experimental tests, for Sellier&Bellot ammunition, maximum projectile velocity is about 409 m/s for ballistic barrel, whereas it is about 348 m/s for HK P7 pistol, which is about 85%. Maximum projectile velocity which can be achieved for ballistic barrel for MESKO ammunition (which was used for tests) is about 360 m/s. Therefore, calculated maximum projectile velocity (which is about 85% of 360 m/s) can be accepted.

3. Gas port diameter and location influence on slide velocity

To check the influence of the gas port: diameter and location on slide velocity, further simulations tests were carried out. Therefore, new values were determined from the reference value. Gas port diameter was changed in the range of 1 to 2 mm every 0.2 mm (reference value 1.4 mm), whereas gas port location was changed in the range of 5 to 12 mm every 1.4 mm (reference value 6.4 mm). The research was carried out in two variants:

- the gas port diameter was changed without changing its position,
- the gas port position was changed without changing its diameter.

The results obtained are presented in Fig. 3-5 and Tab. 3-4.

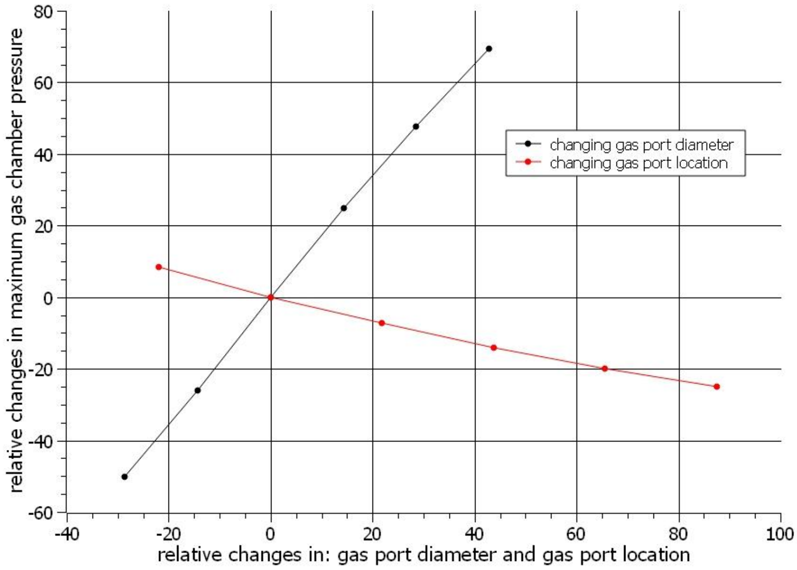

Figure 3. *Relative changes in maximum gas chamber pressure as a function of relative changes in: gas port diameter and gas port location*

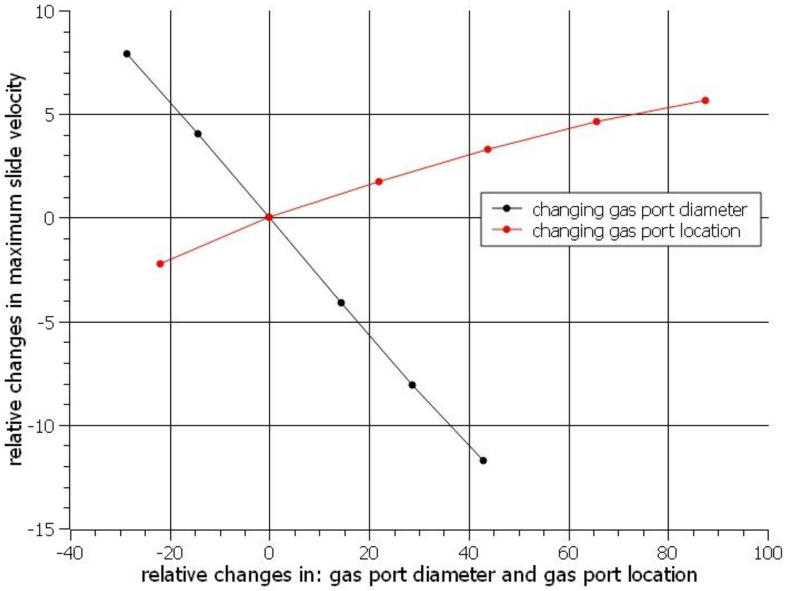

Figure 4. *Relative changes in maximum slide velocity as a function of relative changes in: gas port diameter and gas port location*

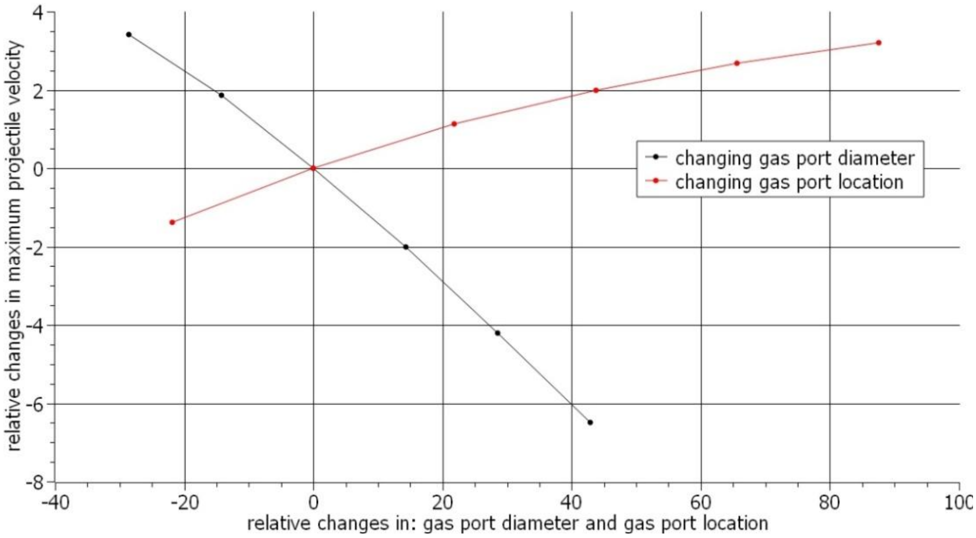

Figure 5. *Relative changes in maximum projectile velocity as a function of relative changes in: gas port diameter and gas port location*

Table 3.

Comparison of some results of numerical simulations for different gas port diameter.

Gas port diameter [mm]	Gas port location [mm]	Maximum barrel bore pressure [MPa]	Maximum gas chamber pressure [MPa]	Maximum slide velocity [m/s]	Maximum projectile velocity [m/s]
1.0	6.4	228.760	11.887	11.22	317.20
1.2		228.748	17.627	10.82	312.45
1.4		228.748	23.843	10.40	306.76
1.6		228.748	29.739	9.97	300.62
1.8		228.748	35.185	9.56	293.87
2.0		228.748	40.357	9.18	286.85

Table 4.

Comparison of some results of numerical simulations for different gas port location.

Gas port diameter [mm]	Gas port location [mm]	Maximum barrel bore pressure [MPa]	Maximum gas chamber pressure [MPa]	Maximum slide velocity [m/s]	Maximum projectile velocity [m/s]
1.4	5.0	221.472	25.825	10.17	302.54
	6.4	228.748	23.843	10.40	306.76
	7.8	229.671	22.099	10.58	310.21
	9.2	229.671	20.504	10.74	312.84
	10.6	229.671	19.101	10.88	314.99
	12.0	229.671	17.889	10.99	316.59

Analysis of the courses of the graphs, it can be concluded that the gas port diameter significantly influences on the characteristics of firearm automatic.

Reducing the gas port diameter by approximately 29% from the reference value reduces the maximum gas chamber pressure by approximately 50% and increases the maximum slide velocity by almost 8%. On the other hand, increasing the gas port diameter by the same percentage value increases the maximum gas chamber pressure by about 48% and reduces the maximum slide velocity by more than 8%. According to the above, the difference of the maximum slide velocity is at the level ±0.8m/s when gas port diameter is ±0,4 mm.

Furthermore, the maximum barrel bore pressure practically is constant despite changing the gas port diameter. However, if the gas port diameter is changed ± 29%, maximum projectile velocity is appropriately higher over 3% and lower over 4%.

Changing the gas port location (projectile travel from the initial position until the bottom of the projectile is in the axis of the gas port) has a slightly smaller effect than the previous changes. It is significant that the most advantageous solution – in terms of slide braking – is gas port made as close as possible to the initial position of the projectile bottom. In spite of that, an absolute limitation in this matter is the length of the cartridge case and the need to make a gas port in front of the front edge of the case. Nevertheless, it should be expected if the gas port location is further increased, the maximum gas chamber pressure will decrease significantly, so that the slide "braking effect" will be increasingly negligible.

Due to preliminary stage, the results of the above studies should be considered a base for the further development of the model and should be validated by the experimental tests. This will allow to make corrections. Furthermore, it was adopted that two gas flow coefficient have value of 1 and their exact values will be determined at the verification stage.

4. Conclusion

Taking into account the presented results of computer calculations and analysis of achieved results, the following conclusions could be drawn:

- The proposed numerical model of gas delayed blowback operation firearm action show decent and satisfactory correctness of the adopted data and assumptions for the preliminary model, but more detailed experimental research is necessary to more accurately verify and validate this mathematical model.
- Thanks to the design and construction of a specialized laboratory stand enabling the measurement of properties for the appropriate parameters it will be possible to validate the model.
- Among the considered parameters of gas delayed blowback operation firearm, the gas port diameter influences significantly on the characteristics of firearm automatic. If we change the diameter by 0.2 mm, the maximum slide velocity changes by more than 0.4 m/s, so it can be important to the au-

tomatic weapon action and to feeling recoil by shooter. On the other hand, in the researched range of changing gas port location it has less significant effect than changing gas port diameter, however it is highly probable that too much increasing projectile travel to gas port will result in a significant less slide "braking effect".

- Simulations using final mathematical model will be a significant source of data and information indispensable to analyze action, simplify and facilitate design of new gas delayed blowback operation firearms.

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