Design of multi-charge gun

Michal Kovarik

***Abstract*—**The multi-charge gun is barrel weapon system comprising more combustion chambers connected to the barrel bore for the purpose of ballistic pressure course improvement and ballistic output increase. The internal ballistics of the gun were described mathematically and examined experimentally with positive results as the basis of formulation of recommendations in explicit form suggested for the utilization in the phase of initial design of the complex multi-variable weapon system.

***Keywords*—**Internal ballistics, mathematical model, multi-charge gun, muzzle velocity, shooting.

I. INTRODUCTION

THE multi-charge gun with multiple powder chambers could be considered as the type of weapon system with separated propellant charge. It is the category of barrel weapons designed to produce higher values of the muzzle velocity by the means of boosting the mean ballistic pressure defined like

$$\overline{p} = \frac{\int_{0}^{l_m} p \, dl}{l_m}, \tag{1}$$

where p does stand for the ballistic pressure, l for projectile travel and l_m represents total projectile travel inside the barrel. The muzzle velocity increase is then possible to inspect in the terms of following simplified relation derived from energy conservation law

$$v_m = \sqrt{\frac{2sl_m}{\varphi\, m_q}\overline{p}}, \tag{2}$$

in which v_m does refer to the muzzle velocity, s to the barrel bore cross-section area, m_q does symbolize mass of the projectile and φ is coefficient of projectile mass fictiveness.

If the level of maximum internal pressure of powder gases rose, the barrel wall strength could be exceeded. Therefore even if the mean pressure is increased, its maximum value must be abided. This requirement is the main reason of "trapezoidal" form of ideal ballistic pressure course illustrated in the following figure.

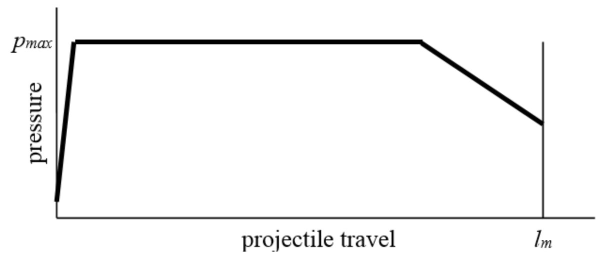

Fig. 1. Trapezoidal pressure course.

Although the early first realization attempts of such a weapon system could be find in 19th century [2,14], the basic principals have not changed. The design of the multi-chambered weapon is distinguished with the use of at least one additional combustion chamber placed alongside the barrel bore compared to typical barrel weapons. The additional propellant charge is being placed inside the additional chamber(s). Additional chamber is connected with the internal space of the barrel by the blaze-through channels. The process of shot generation begin ordinarily with initiation of basic propellant charge of mass ω_1 in combustion volume $c_{0,1}$, produced gases presses projectile through the bore to the distance l_1, where projectile passes and opens the mouth of the connecting channel cross-section surface S_{kr}. Hot gases intrude into additional chamber of volume $c_{0,2}$ and ignite the additional charge of mass ω_2. During the burning of additional charge the gas flow from additional chamber to the bore should form and contribute to the ballistic pressure and projectile acceleration. The situation is illustrated in following figure.

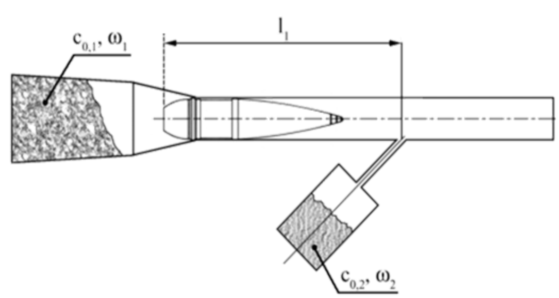

Fig. 2. Scheme of multi-chamber gun with one additional chamber.

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There could be placed more additional chambers as well as the ignition of the additional propellant charge could be made by individual initiator with driven ignition delay.

If such a modification of the weapon system resulted in the pressure course shape close enough to the ideal one, the obtained muzzle velocity increase could be expected as high 30 % according to the relation (2) in the case of typical gun values together with published results in [4], [10] or [14].

II. Problem Solution

A. Mathematical model

Following the objective of description of the barrel weapon interior ballistics processes the mathematical model have had to be assembled. The core of the model is based on the thermodynamic description ([1], [2], [3], [4], [5] or [9]) of geometrical propellant combustion theory consisting of lumped-parameter system of following equations:

- the equation of propellant gases generation describing dependency of relative quantity of burnt-out powder ψ on the relative burnt thickness of the powder grain z and geometric characteristics of powder grain κ, λ, μ:

$$\psi = \kappa z + \kappa\lambda z^2 + \kappa\mu z^3 ; \tag{3}$$

- the formula for ballistic pressure derived from the equality of energy and work done by propellant gases:

$$p = \frac{f\omega\psi - \frac{1}{2}\Theta\varphi m_q v^2}{s\left(l_\psi + l\right)} , \tag{4}$$

  where f represents specific energy of propellant;

- the equation of motion of the projectile:

$$\varphi m_q \frac{\mathrm{d}v}{\mathrm{d}t} = sp ; \tag{5}$$

- the relation for propellant grain burning rate given by exponential burning law described by coefficients of burning m and ν, the unitary rate of burning u_1 and the total pressure impulse of ballistic pressure I_k:

$$\frac{\mathrm{d}z}{\mathrm{d}t} = \frac{u_1\left[m + p^\nu\right]}{I_k} ; \tag{6}$$

- the relative length of combustion volume l_ψ formula characterizing the amount of 'free' space behind the projectile:

$$l_\psi = l_0\left[1 - \frac{\Delta}{\delta} - \Delta\psi\left(\alpha - \frac{1}{\delta}\right)\right] , \tag{7}$$

  where l_0 represents its initial value without the propellant, Δ stands for the loading density, δ for the powder mass density and α is the covolume of powder gases;

- the supplementary equation of projectile kinematics:

$$\frac{dl}{dt} = v ; \tag{8}$$

- the equation from which describes temperature as a function of relative quantity of burnt-out powder ψ and velocity of projectile v:

$$T = T_V\left[1 - \frac{1}{\psi}\left(\frac{v}{v_{\lim}}\right)^2\right], \tag{9}$$

  where T_V represents explosion temperature of powder and v_{lim} stands for the limiting velocity of projectile for the considered weapon system.

This model of the interior ballistics has to be modified in order to describe the weapon utilizing additional chambers. Most important adjustments concerns separate description of every combustion space (deduced from the same assumptions), implementation of Dalton's law for propellant gases mixture and the crucial assessment of the propellant gases flow rate m_{pr} between the chamber and barrel bore, which could be quantified as

$$m_{pr} = \xi\kappa_k S_{kr} \frac{p}{\sqrt{f\frac{T}{T_v}}} , \tag{10}$$

where the coefficient κ_k defines local flow conditions of the particular channel design (it can be assessed according to the Cibulevsky theory) and ξ represents outflow coefficient equal to

$$\xi = \sqrt{\Theta + 1}\left(\frac{2}{\Theta + 2}\right)^{\frac{\Theta+2}{2\Theta}} , \tag{11}$$

when velocity of the flow is critical, if not its value is solved by means of relation

$$\xi = \sqrt{\frac{2\left(\Theta+1\right)}{\Theta}\left[\left(\frac{p_1}{p}\right)^{\frac{2}{\Theta+1}} - \left(\frac{p_1}{p}\right)^{\frac{\Theta+2}{\Theta+1}}\right]} . \tag{12}$$

The solution of the presented system could be found by the numerical method only. The Runge-Kutta 4th order method has been used and the appropriate procedures were built in the environment of Matrix Laboratory software.

B. Experimental shootings

In order to consider the validity of the model experimental shootings have been carried out.

The used ballistic barrel of 12.7mm calibre and length of 100 calibres was adapted by the manufacturing triplet of connecting channels to additional chambers and matching supportive bearers for additional chambers. The volumes of additional chambers were manufactured inside the hollow screws (see Fig. 4). Scheme of weapon can be found in following figure.

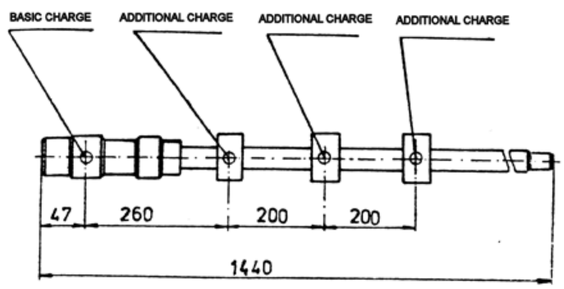

Fig. 3. Chambers placement alongside the barrel bore.

The experimental ammunition does consist of projectile, basic charge and additional charge. Types of monolithic brass projectiles were being designed instead of the common line 12.7×107 production because of the mass variation and repeatability of shots. The basic charge was placed inside the steel cartridge case adjusted to the pressure measurement according to C.I.P. standards. The propellant was 7-hole single based deterred powder (Nc 7d). The double-based small-grained spherical powder with the higher vivacity (D032) was used as the additional propellant. Because of the manipulation reasons it was placed inside the combustible micro-foil perforated bag.

The timed ignition of additional charge was also examined. Therefore the electric initiator F3 (EMS PATVAG) was placed in the hollow volume of the support casing, together with composite contact casing of crezol-formaldehyde resin and the assembly of contact pin placed inside the composite. In the case of ‘gas ignition’ the assembly without electric equipment was used.

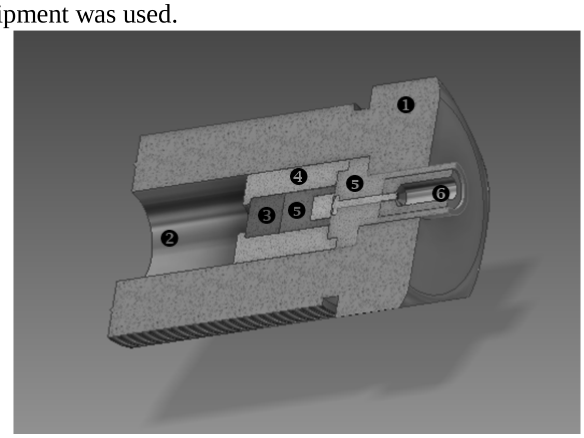

Fig. 4. The additional charge assembly (1 – body of the additional chamber screw, 2 – combustion volume, 3 – initiator F3, 4 – metal casing sleeve, 5 - resin insulator casing, 6 – firing contact pin assembly) .

The arrangement of the measuring chain is depicted in the figure just below. The operation started by the time delay setup on the timing unit from personal computer by the means of the developed digital interface. Then the sufficient electric charge was stored in the capacitive high-voltage unit. The mechanical initiation of the basic propellant charge caused the rise of the ballistic pressure. The value of the pressure was measured by the piezoelectric sensor. The charge signal was transformed to voltage signal and observed by the timing unit in real-time. After the pressure threshold was reached, the timing unit counted the delay and sent the control signal to the switch unit. The high-voltage circuit was closed and initiator ignited the additional propellant. The laser gates were used to measure projectile velocity and ballistic analyzer filtered, digitalized and recorded signals.

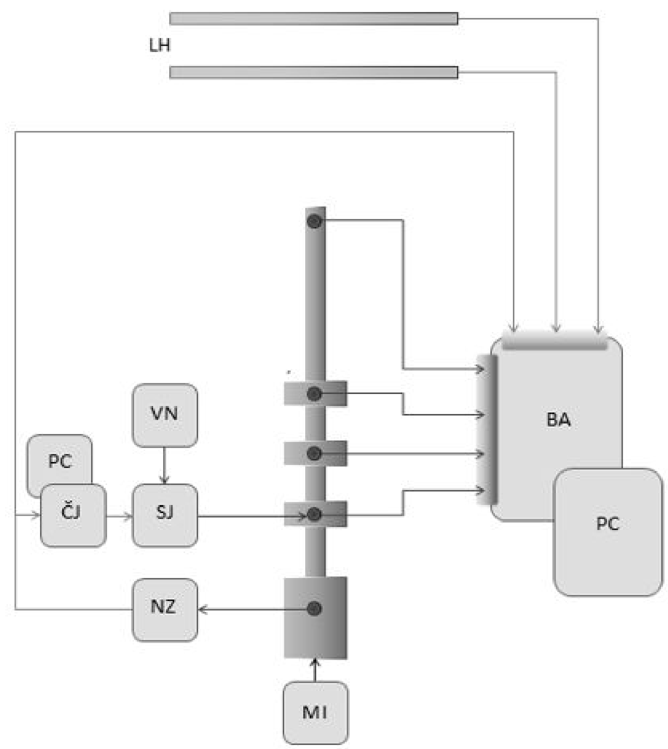

Fig. 5. The measuring chain (PC-personal computers, BA-ballistic analyzer, NZ-charge-voltage transducer, ČJ-timing unit, SJ-switch unit, VN-high voltage unit, LH-laser gates, arrows-signal lines, dots – pressure sensors).

C. Results

The resulting pressure courses for cases of modelled weapon without additional charge and both modelled and tested weapon with the utilization of one additional charge ignited timely could be observed in the following figure and gained values of maximum pressure and muzzle velocity are enumerated in next table.

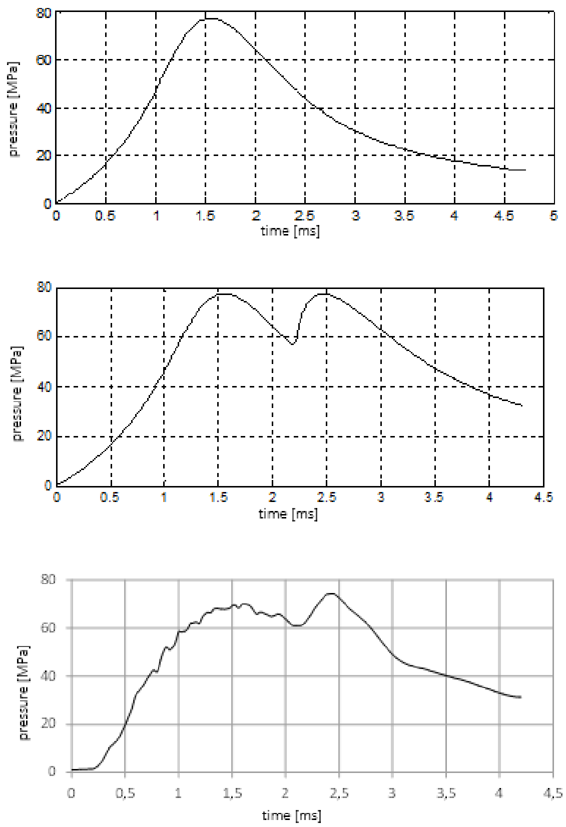

Fig. 6. Pressure courses (model of typical gun – upper, model of gun with one additional chamber – middle, measurement of gun with one additional chamber).

TABLE I. COMPARISON BETWEEN TYPICAL GUN AND GUN WITH ONE ADDITIONAL CHAMBER.

Powder charge		Experiment		Model	
basic	*additional*	p_m [MPa]	v_3 [m·s^{-1}]	p_m [MPa]	v_m [m·s^{-1}]
9 g Nc7d	-	76,7	544,2	77	545
9 g Nc7d	1,7 g D032, ignit. delay 1125 μs	76,9	612,9	77	633

The multi-chambered weapon system with ignition of propellant charge by hot propellant gases only under different configurations (up to 3 additional chambers and different projectile used) provides following tabulated results.

TABLE II. RESULTS FOR GUN WITH IGNITION BY HOT GASES

Powder charge (basic + additional)	Experiment		Model	
	p_m [MPa]	v_3 [m·s^{-1}]	p_m [MPa]	v_m [m·s^{-1}]
9 g Nc7d	103	505	104	509
9 g Nc7d + 1 g D032	107	541	104	552
9 g Nc7d + 2 g D032	124	608	111	602
9 g Nc7d + 1 g D032 + 1 g D032	98	560	104	576
9 g Nc7d + 1 g D032 + 1 g D032 + 1 g D032	109	582	104	589

The given weapon system of multi-chamber gun was able to produce approximately 15 % higher muzzle velocity and the model ability to predict results could be considered as admissible.

D. Analysis of attainable velocity

The model has been set to solve the task repeatedly with varying inputs to work out numerical sensitivity analysis. The influence on the muzzle velocity of the placement of additional chamber, the number of additional chambers, the cross-section area of connection channel, the volume of additional chamber, mass of the additional charge and selected properties of the propellant grains has been observed.

The placement of the additional chambers (the length of projectile trajectory to the embouchure of flash holes more precisely) affects the values of muzzle velocity significantly. The lower bound for this distance is the projectile travel l_m, where the maximum of ballistic pressure of basic charge is reached. Closer placement of additional chamber usually results in enormous pressure growth. If the size of l_m is not known, it could be guessed by Chabonnier-Sugot method by

$$l_m = \frac{c_0}{s}\left(1-\alpha\Delta\right)\left[\left(\frac{2\kappa}{\kappa+1}\right)^{\frac{2}{\kappa-1}}-1\right]. \tag{13}$$

If the approximate effect of additional chamber placement assessment would be based on the idea of simple proportional use of the propellant chemical energy, then the dependency of obtained muzzle velocity v_i on the distance of the additional charge placement l_i is deduced in the form

$$v_i = v_0\sqrt{1+\frac{\omega_i f_i}{\omega_0 f_0}\left(1-\frac{l_i}{l_m}\right)}, \tag{14}$$

where ω_i represents the mass of the additional propellant charge and f_i specific energy of its propellant.

The simplified solution versus numerical analysis of the system could be observed in the Fig. 7.

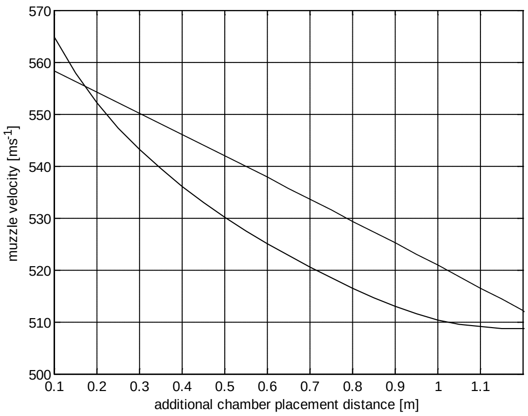

Fig. 7. Influence of additional chamber placement on muzzle velocity (numerical solution – solid line, simplified solution – dotted line).

If the case of the basic design of evenly-spaced additional chamber is considered and the condition of non-breaching the pressure limit is fulfilled, the effect of number of additional chambers augmentation on the muzzle velocity could be observed in the following figure (solid line).

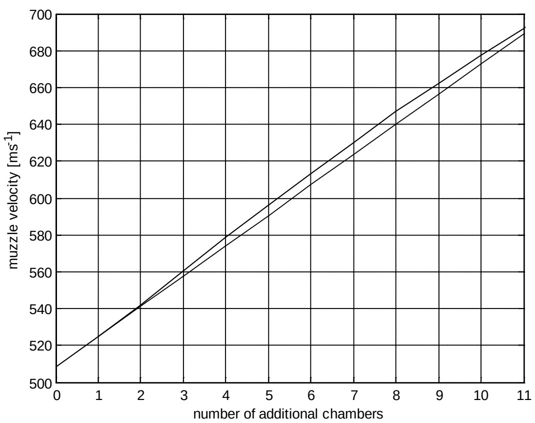

Fig. 8. Influence of evenly-spaced additional charges on muzzle velocity (robust solution – solid line, simplified solution – dotted line).

The observed course revealed almost constant value of the first derivative which could be used to simplified solution if the effect of at least one additional chamber was known in the form

$$v_i = v_0 + \left(v_1 - v_0\right) \cdot j \,, \tag{15}$$

where v_i is value of increased muzzle velocity, v_0 projectile velocity of pure system with basic charge only, v_1 velocity with one additional chamber and j is the number of additional chambers.

The latter variant of variable placing of chambers ordinary distinguishes with higher ballistic efficiency. The gain in projectile velocity could be guessed by the use of (16), however it was revealed that the suitability of formula decreases with numbers of additional chamber higher than three.

The “ideal” multi-charge weapon of infinite number of additional chambers and no heat losses resulting in isobaric pressure course, would reach the muzzle velocity of the projectile

$$v_{\max} = \sqrt{2\frac{sl_m p_{\max}}{\varphi m_q}} \,, \tag{16}$$

which represents velocity upper constraint. Therefore the simplified estimation of the muzzle velocity is equal to $\min(v_i, v_{\max})$.

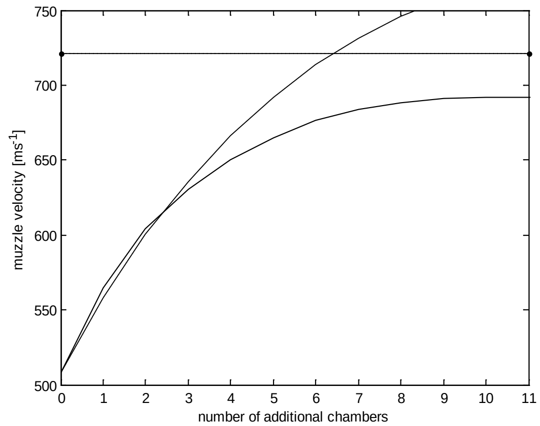

Fig. 9. Muzzle velocity vs. number of additional chambers (numerical solution – solid line, constraint value – slash-dot line, siplified formula – dotted line).

The section area of the flash hole connecting the additional chamber with barrel bore does affect the flow rate of the propellant gases according to (10). On that basis it could be expected that the bigger the cross-section induce the higher projectile velocity due to higher flow rate from chamber to volume, but the situation is not completely unequivocal, because larger section area also produce more intensive gases detraction from bore and decreases burning rate inside the additional chamber.

The numerical analysis of the current weapon system reveals that there is the optimal value of the ratio flash hole cross-section area to barrel bore cross-section area (see Fig. 10). The similar values of the ratio closed to the 50 % are obtained when all small arms systems are considered.

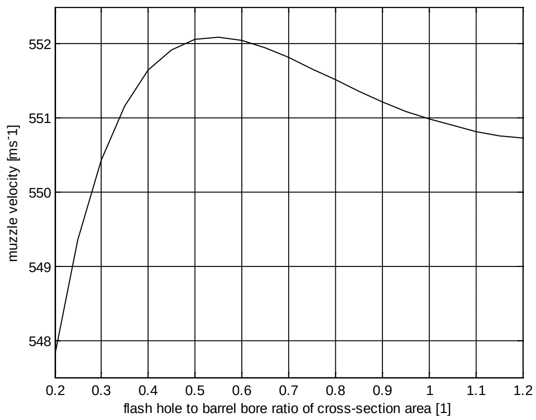

Fig. 10. Muzzle velocity vs. flash hole to barrel bore ratio of cross-section area.

There is also crucial design requirement of maximal pressure burden of the additional chamber, for that reason the maximum value of ballistic pressure within the volume of additional chambers has to be calculated and checked. The adequate simplified optimistic guess is expressed like (indexes *i* refers to *i*-th additional chamber)

$$p_{m,i} = \frac{f_i \omega_i - f_i Z_i S_{kr,i}}{c_{0,i} - \alpha_i \omega_i + \alpha_i Z_i S_{kr,i}}, \tag{17}$$

where the expression Z_1 could be considered as a constant and equal to

$$Z_1 = \frac{\sqrt{\Theta_i + 1}}{\sqrt{f_i}} \left(\frac{2}{\Theta_i + 2} \right)^{\frac{\Theta_i + 2}{2\Theta_i}} I_{k,i} \mu \varphi_r \,. \tag{18}$$

The volume of the additional chambers is always related to the mass of the additional charge. The volume c_{0i} should be at least sufficient enough to accommodate the charge

$$c_{0i} \geq \frac{\omega_i}{\Delta_{i\,\max}} \tag{19}$$

Generally the muzzle velocity decreases with the additional combustion chamber increase. The simplified guess based on the idea of the transfer of mechanical work done by propellant gases into the kinetic energy of the projectile is given by

$$v_{\acute{u}1} = v_{\acute{u}} \sqrt{\frac{\ln\left(\frac{sl_1 + c_{0z}}{c_{0z}}\right) + \left(1 + \frac{f_1 \omega_1}{f_z \omega_z}\right) \ln\left(\frac{sl_{\acute{u}} + c_{0z} + c_{01}}{sl_1 + c_{0z} + c_{01}}\right)}{\ln\left(\frac{sl_{\acute{u}} + c_{0z}}{c_{0z}}\right)}}, \tag{20}$$

but it provides very rough presumption (difference almost 4 % in the case of studied weapon system, see Fig. 11). Nevertheless the slope of the course is consistent with the numerical solution and could be applied.

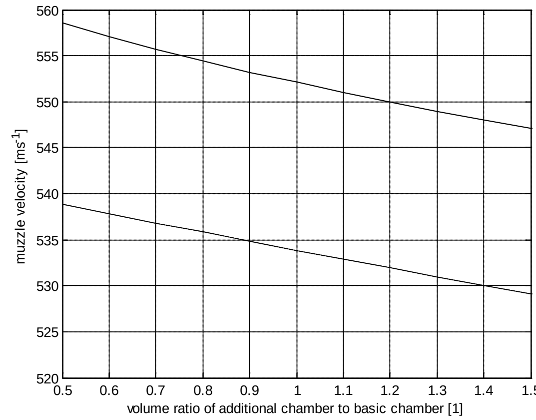

Fig. 11. Muzzle velocity vs. ratio of additional chamber volume to basic chamber volume (robust solution – solid line, simplified solution – dotted line).

The propellant powder type selection usually depends on the fundamental property of the smokeless powder, the specific energy of the propellant (“powder force”). The assessment of the suitable specific energy of the propellant could be done by the means of the equation (14), comparison with the numerical solution is depicted in the Fig. 12 for the specific energy ratio of the additional charge to basic charge.

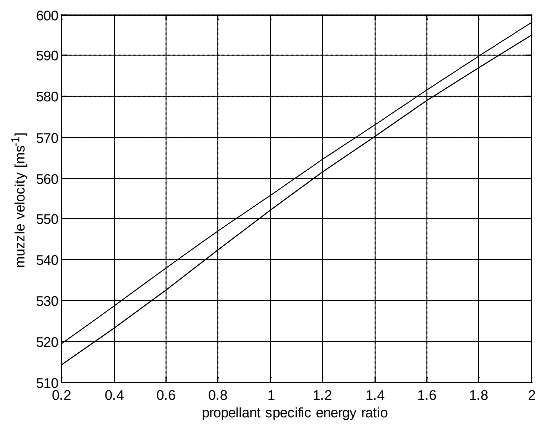

Fig. 12. Muzzle velocity vs. specific energy ratio (robust solution – solid line, simplified solution – dotted line).

The mass of the additional charge should straightforwardly concordantly affect the muzzle velocity. For the initial quantification can be used equation (20) as it is shown in the Fig. 13 below.

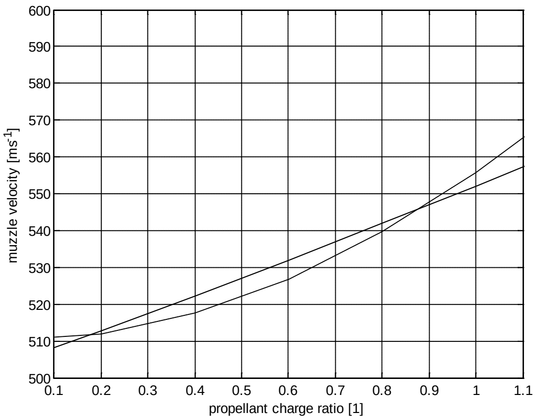

Fig. 13. Muzzle velocity vs. ratio of mass of additional propellant charge to basic charge (robust solution – solid line, simplified solution – dotted line).

It shall be necessary to avoid the solution by the equations utilized in the case of internal ballistics of closed vessels, such as

$$\Delta = \frac{p_{\max}}{\alpha\, p_{\max} + f} \tag{21}$$

because the charge would remain underestimated significantly due to neglected outflow.

The influences of the mass of the additional propellant charge and the combustion volume of the additional chamber are antagonistic, for that reason it is better to study them combined in the phase of the initial design of the multi-chamber gun. Isotachs were calculated for the given weapon system and depicted in following figure in the plane defined by ratios of propellant masses (the mass of additional propellant to the mass of the basic charge) and combustion volumes (the volume of additional chamber to the initial combustion volume of basic charge) and could be used for choosing suitable value of additional charge loading density.

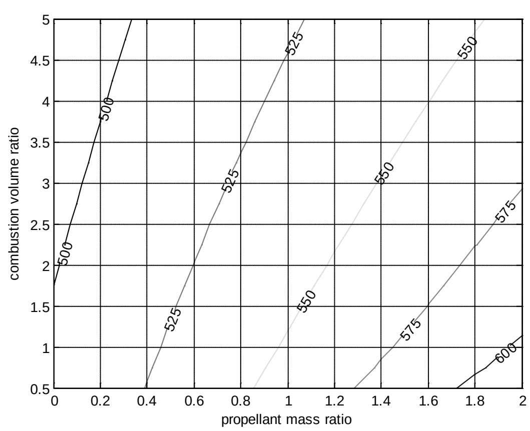

Fig. 14. Izotachs of experimental system (velocities in [ms^{-1}]).

III. Conclusion

The results of analysis made could be summed up in the several simplified principles that should be followed in phase of initial design of multi-chamber guns, the selected substantial ones are as follows:

- additional chambers could be designed uniformly as well as additional propellant charges without significant depreciation of the advantages of multi-chamber gun system, the closer is chamber situated to the muzzle the smaller effect is usually observed;
- the volume of additional chamber should be designed with respect to mass of the additional charge and usually smaller volumes produce better outputs, volume should be bulky enough in order to not exceeding maximum allowed pressure;
- the first additional chamber should be placed closely after the place, where the maximum pressure of basic charge is reached;
- the cross-section area of the connection blaze-through channel should be as large as the barrel bearability does allow;
- the powder of additional charge should be characterized with higher vivacity than the powder of the basic charge;
- the use of jacketed types of projectiles could cause difficulties during passing the mouth of the connection channel mouths.

The expected pressure course of the multi-chamber gun in the case of use six uniformly designed additional chambers supplementing the original weapon is depicted in following figure (compare to Fig. 1), expected velocity increase is 25 per cent.

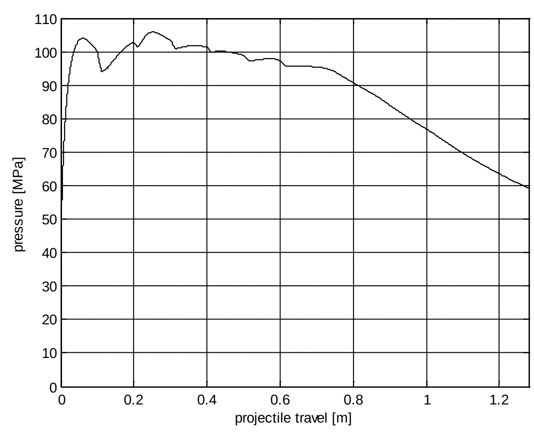

Fig. 15. Modelled pressure course of multi-chambered gun.

Because of safety reasons and developed wear of the experimental weapon only the limited number of shots with restricted power output could be fired, in order to confirm the results in the wider interval of inputs the more extensive experimental work should be done especially testing on the edge of the maximum ballistic performance.

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