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# Determination of the propellant combustion law under ballistic experiment conditions

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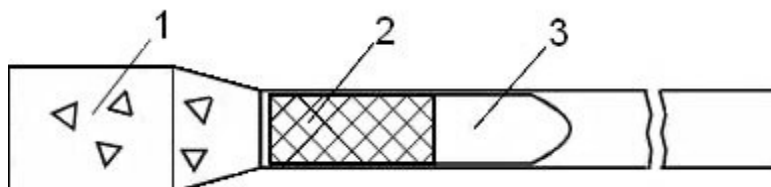
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**Abstract.** The main characteristics of ballistic experiment are the maximum pressure in the combustion chamber  $P_{\max}$  and the projectile velocity at the time of barrel leaving  $U_M$ . During the work the burning law of the new high-energy fuel was determined in a ballistic experiment. This burning law was used for a parametric study of depending  $P_{\max}$  and  $U_M$  from a powder charge mass and a traveling charge at initial temperature of + 20 °C was carried out. The optimal conditions for loading were obtained for improving the muzzle velocity by 14.9 %. Under optimal loading, there is defined the conditions, which is possible to get the greatest value muzzle velocity projectile at pressures up to 600 MPa.

## 1. Introduction

In the internal ballistic design of artillery systems, various approaches to increasing the projectile velocity at the exit from the barrel are being investigated. One such approach is throwing a projectile using a traveling charge (TC). This work contributes to the improvement of traditional artillery weapons.

There are classical and non-traditional schemes of throwing. In the classical throwing scheme, the projectile acceleration occurs only due to the powder charge combustion in the chamber. One of the non-traditional schemes of throwing is a scheme with a TC. In this scheme, perspective high-energy convective combustion propellants are used as a traveling charge. The traveling charge is located directly behind the projectile and they move together along the barrel channel, forming a two-body system Projectile + TC. Figure 1 shows that, during motion along the cylindrical channel, the projectile is exposed by gases with gradual fuel combustion in two regions where the traditional powder charge and TC are located.



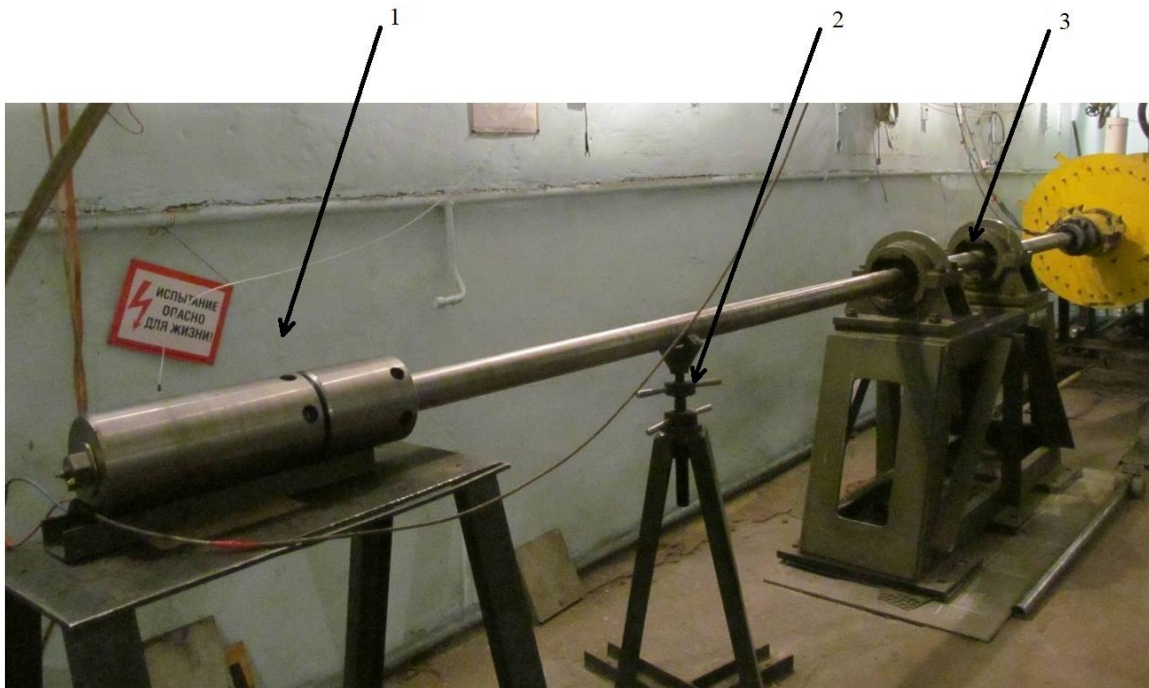
1 – Conventional powder charge,  
2 – traveling charge, 3 – projectile,  
Figure 1 – General scheme of throwing with TC

Initially, the main powder charge is ignited in the combustion chamber. The projectile starts to move, and after some time called the ignition delay time, the traveling charge ignites and burns from the end remote from the projectile. In the acceleration process the throwing gas pressure changes due to two main factors. The gases arrival due to propellant elements burning increases the pressure, and the increase of volume behind the projectile reduces it. Maintenance of pressure at a sufficiently high level is possible by using progressive combustion elements in the propellant charge. In this respect, new pasty progressive combustion character propellants have great prospects.

Thus, the use of TC allows to increase the muzzle projectile velocity without increasing the maximum chamber pressure. This is achieved by propellant charge energy increasing, increasing the pressure in the barrel depth directly in space behind the projectile and reactively projectile driving, which appears due to the TC combustion products outflow.

The purpose of this paper was to determine the combustion law of a promising high-energy propellant in a ballistic experiment at a standard laboratory temperature of  $+20\text{ }^{\circ}\text{C}$ . Also there is a pursuance of the parametric research of the connection between loading parameters and ballistic parameters of the experiment. This study will assess the new propellant potential of projectile velocity increasing, as well as enter into work about a temperatures effect on the processes of throwing.

The main task of this study was to determine by how many percent the muzzle projectile velocity can be increased in a pressure range up to 600 MPa, permissible for the particular ballistic installation, and the necessary loading conditions.



1 - Combustion chamber,  
2 - Breech support,  
3 - Carriage,

Figure 2 – Ballistic installation

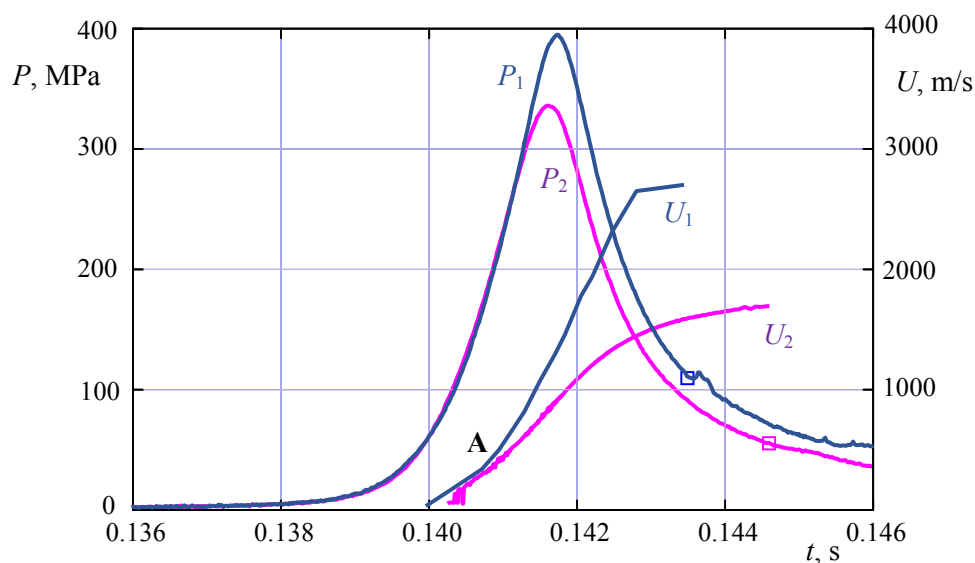
## 2. Experimental data processing

The main thermodynamic characteristics of propellants and combustion products: density, combustion temperature, force, covalent, adiabatic index and molecular weight are determined by the manufacturer. The law of propellant combustion under the closet vessel conditions is also defined.

However, for a more detailed study of propellant, there is a need to determine the propellants combustion law in the ballistic experiment, because combustion may be different.

Figure 2 shows a ballistic installation where laboratory experiments on classical and non-traditional throwing schemes were conducted during the work in the 70th department of the RIAMM TSU. A pressure in the combustion chamber  $P(t)$  and a maximum pressure in the chamber  $P_{max}$ , a velocity of the projectile as it travels along the barrel channel  $U$  and at the moment of barrel departure  $U_M$  were measured in experiments. The inert projectile used in the whole experiments series had a fixed mass. A granular powder charge was used as the main charge in the chamber. The TC made from the perspective paste propellant was placed in a polyethylene container. From one end the container is covered with a grid, which prevents the propellant from escaping. In experiments on the classical throwing scheme, a polyethylene imitator of the same mass and size as the TC in the container was used. Thus, the starting assembly mass, the initial projectile element position and, consequently, the pressure of forcing  $P_f$  (the pressure when the projectile was struck) was preserved in the all series of experiments.

Figure 3 shows the relationship between the combustion chamber pressure and the projectile as a function of time for different throwing schemes. As it can be seen the projectile velocities are practically the same at the initial stage. A point A is a moment of the rapid increase in the velocity, which corresponds to the onset of TC combustion.

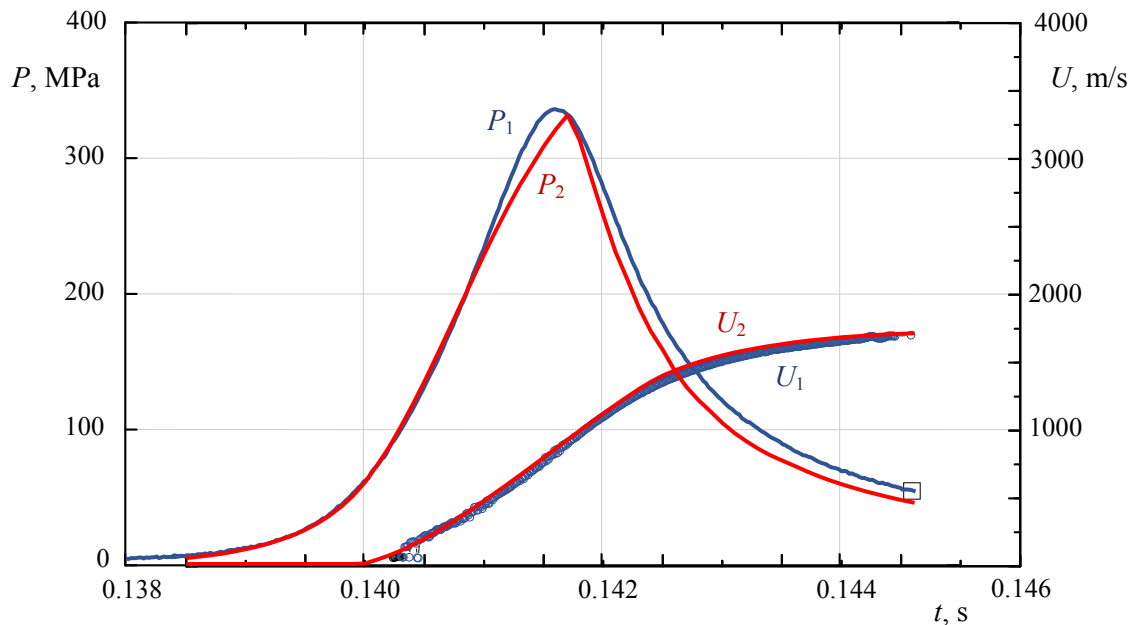


**Figure 3.** Projectile pressures and velocities dependences of time in experiments with the initial charge temperature  $+20^{\circ}\text{C}$   
1 – non-traditional scheme with the TC, 2 – classical and scheme

A mathematical model developed in the 70th department of the RIAMM TSU was used to investigate the above throwing scheme. This model allows to solve the direct internal ballistics problem for various throwing schemes, to determine the projectile pressure and velocity for the specified parameters of the installation, charge and projectile. A special program complex [2], developed in the 70th department of the RIAMM TSU, was used for calculations.

At the first stage of the experimental data analysis, there was determined friction of barrel motion  $\tau$ . Such parameters are determined as matching parameter of the experimental and calculated data based on experiments with the imitator. It est during the series of calculations, this parameters are

changed in certain range to achieve the maximum coincidence of the experimental (in Tables 1 and 2 are denoted by  $P_e$ ,  $U_e$ ) and the calculated values (denoted by  $P_c$ ,  $U_c$ ) of  $P_{\max}$  and  $U_M$ , and respectively curves  $P(t)$  and  $U(t)$ , as shown in Fig. 4. The standard gunpowder charge parameters are used.



**Figure 4.** Typical plot of the chamber pressure ( $P$ ) and the projectile velocity ( $U$ ) versus time for the classical scheme of throwing  
1 – experiment, 2 - calculation

Table 1 presents the matching parameters of the classical throwing scheme obtained in the calculation of the experiments at the standard temperature  $T_1 = 20$  °C, and the difference between the calculated and experimental values of the maximum pressure ( $\Delta P_{\max}$ ) and the muzzle velocity of the projectile ( $\Delta U$ ). Then the parameters were used in all calculations to determine the propellant combustion law used as the TC in a non-traditional throwing scheme.

**Table 1.** Matching parameters of the classical throwing scheme

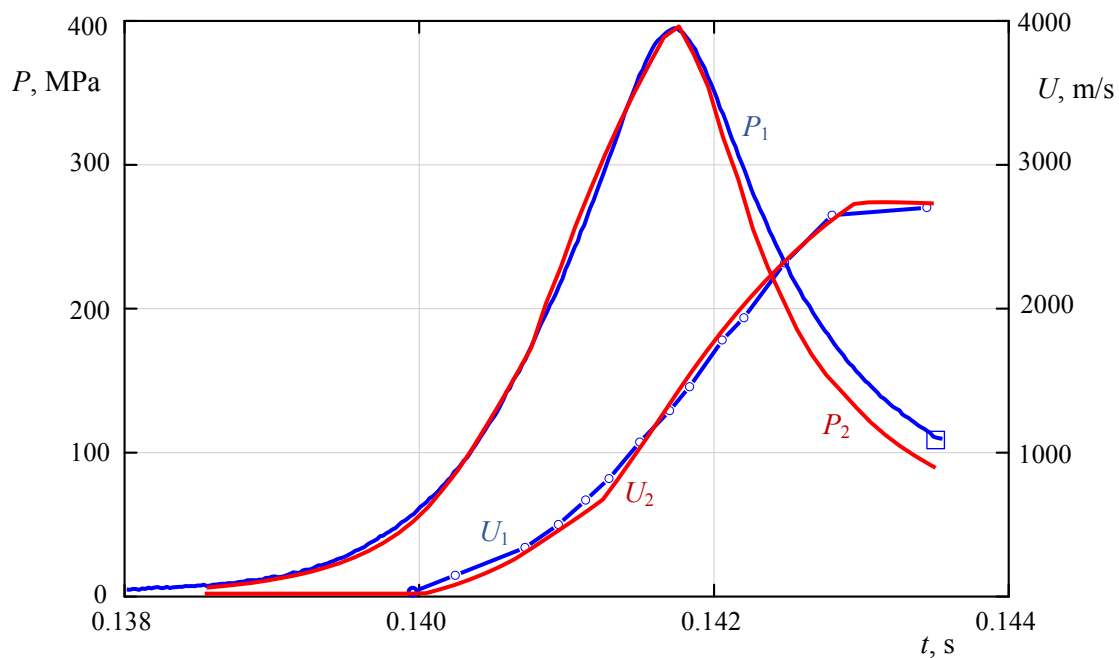
$P_t$ , MPa	$\tau$ , MPa	$\Delta P_{\max}$ , %	$\Delta U$ , %
60	1	0.77	0.3

While the theoretical analyzing the gunpowder charge in the chamber is believed instantly ignites and burns at known linear velocity. The TC ignites after a certain time of gunpowder combustion. TC Combustion is determined by the impulse, which is calculated by the formula (1):

$$I = \int_0^t P dt \quad (1)$$

were  $u$  – combustion rate,  $B_i$  – velocity coefficient,  $P$  – pressure behind the combustion front,  $v_b$  – power factor.

an explosion point is set by the ignition delay impulse  $I = I_1$ . The TC combustion is characterized by two periods of slower combustion with a velocity  $u = B_1 \cdot P^{\nu}$  and faster combustion with a velocity  $u = B_2 \cdot P^{\nu}$ . A transition moment is determined by reaching the pulse value of the accelerated combustion impulse  $I = I_2$ . The combustion law parameters as  $I_i$ ,  $B_i$  depend on the fuel properties and they were determined as matching parameters of the experimental and calculated data (Fig. 5). Table 2 gives the obtained parameters of the combustion law.



**Figure 5.** Typical plot of the chamber pressure ( $P$ ) and the projectile velocity ( $U$ ) versus time for the scheme with TC  
1 – experiment, 2 - calculation

**Table 2.** Matching parameters for nontraditional scheme throwing with TC

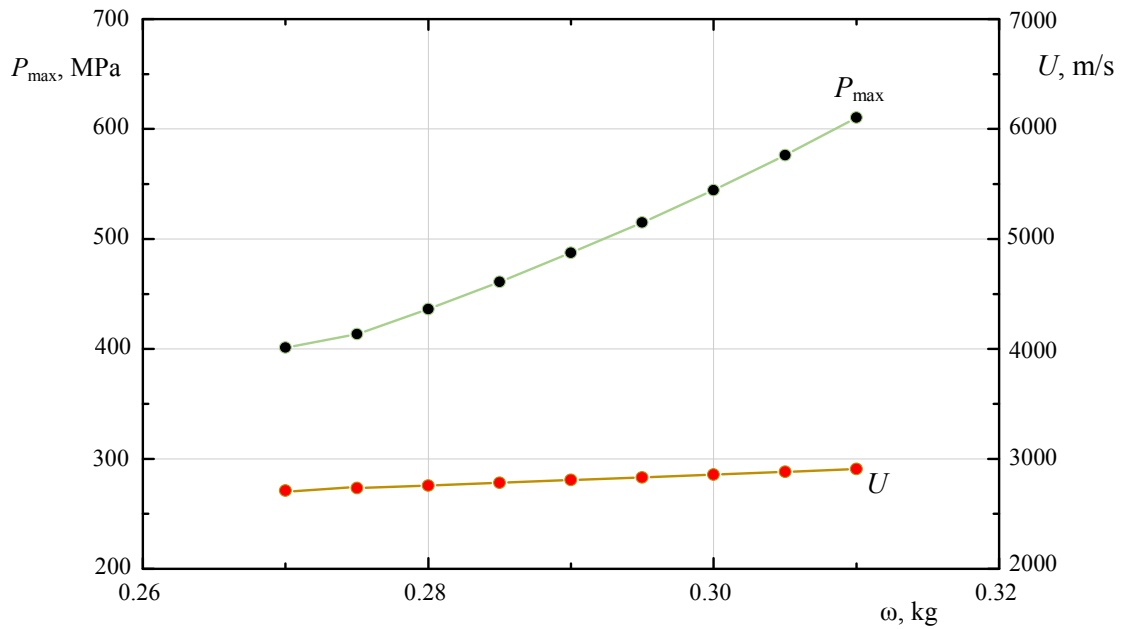
$B_1$ , $\text{m/s}/(0.1 \cdot \text{MPa})^{\nu_1}$	$I_1$ , $\text{MPa} \cdot \text{s}$	$B_2$ , $\text{m/s}/(0.1 \cdot \text{MPa})^{\nu_2}$	$I_2$ , $\text{MPa} \cdot \text{s}$	$\Delta P_{\max}$ , %	$\Delta U$ , %
0.0045	0.0865	0.024	0.19	0.7	0.3

The patterns of throwing obtained during the processing of experiments can be considered valid, since the discrepancy between the experimental and calculated values does not exceed 0.77%. These matching parameters were used to further investigation the relationship between the loading parameters and the muzzle velocity of the projectile.

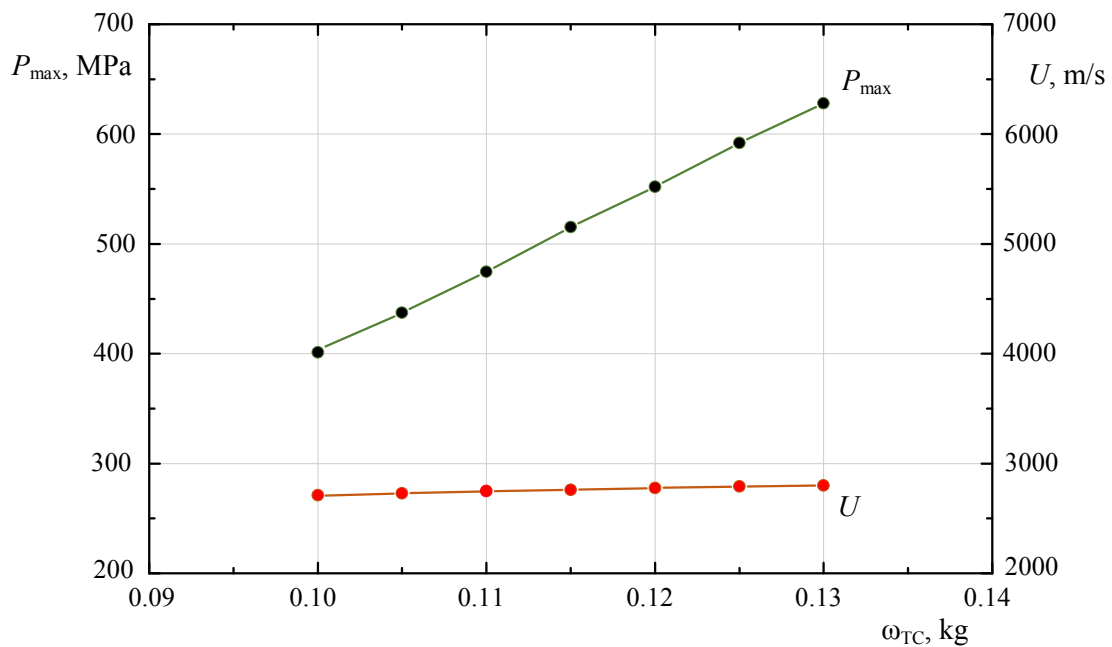
### 3. Parametric investigation of the loading parameters

Using the obtained combustion law, parametric investigations were performed during which the mass of the powder charge in the chamber (Fig. 6) and the mass of the attached charge (Fig. 7) varied. The mass of the projectile and the TC remained unchanged. In the permissible pressure range (600 MPa), the velocity does not practically change, regardless of how much the mass of the powder or the TC

increases. This is due to the TC combustion with such a velocity that the propellant doesn't have time to burn up before the projectile leaves the barrel.



**Figure 6.** Dependence of the maximum pressure and muzzle velocity of the projectile on the change in the mass of the powder charge in the chamber

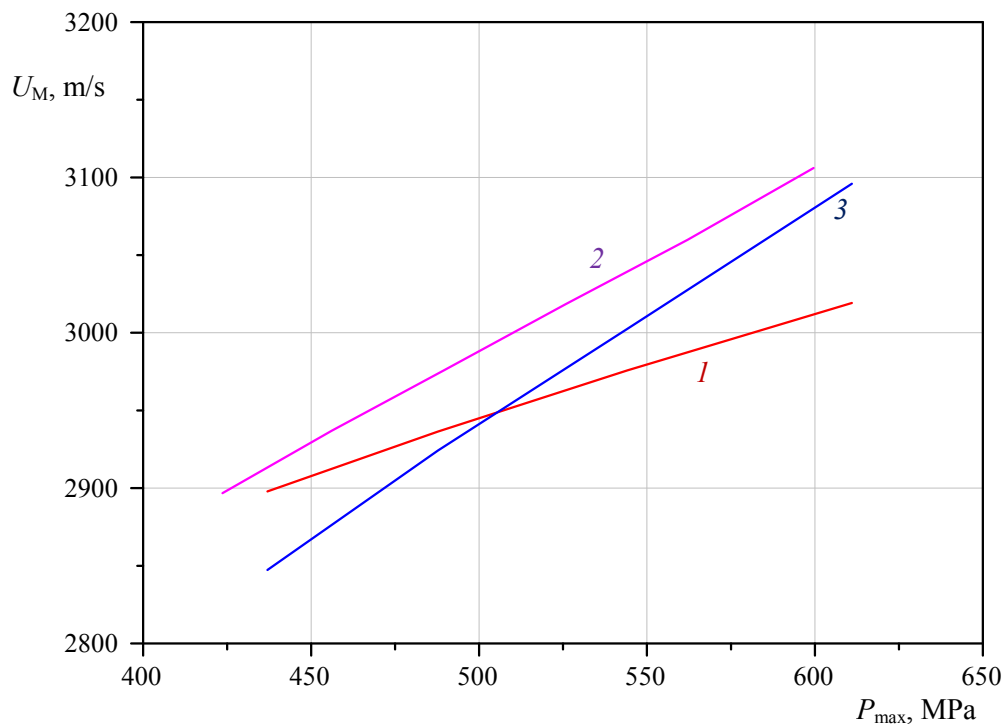


**Figure 7.** Dependence of the maximum pressure and muzzle velocity of the projectile on the change in the mass of the TC

In connection with the characteristics of propellant combustion, the optimum result by using the TC is obtained when the ignition of the TC occurs after the pressure peak. There are mechanical and chemical mechanisms for delay, but the most practical one should be considered the chemical retarder design. In the calculations, the presence of the chemical retarder is modeled by the accelerated combustion impulse  $I_2$ . In the course of the study, the delay impulses changed along with the mass of the gunpowder and TC, the variation in muzzle velocity and maximum pressure in the combustion chamber was checked.

Figure 8 shows the dependence of the maximum possible velocity on the specified maximum pressure in the chamber at  $T_0 = 20\text{ }^\circ\text{C}$ . Thus, Figure 8 demonstrates the optimal accelerated combustion impulses  $I_2$  selected for the initial temperature of the charge  $+20\text{ }^\circ\text{C}$ . At these impulses the best initial velocity values in the admitted pressure range are reached. Line 1 is the results obtained by changing the mass of the gunpowder charge in the chamber at the constant mass of the TC,  $I_2 = 0.26\text{ MPa}\cdot\text{s}$ . Straight lines 2 and 3 are the results obtained with the constant mass of the powder charge in the chamber and with TC mass changing, the accelerated combustion impulses  $I_2$  are respectively  $0.26\text{ MPa}\cdot\text{s}$  and  $0.3\text{ MPa}\cdot\text{s}$  respectively.

It can be seen that the variation of the impulse  $I_2$  makes it possible to increase the maximum possible velocity at the particular maximum pressure in the chamber.



**Figure 8.** Dependence of the initial velocity on the maximum pressure at different impulses  $I_2$ , gunpowder mass and TC mass ( $T_0 = +20\text{ }^\circ\text{C}$ )

1 –  $I_2 = 0.26\text{ MPa}\cdot\text{s}$ ; 2 –  $I_2 = 0.26\text{ MPa}\cdot\text{s}$ ; 3 –  $I_2 = 0.3\text{ MPa}\cdot\text{s}$

#### 4. Investigation results

The complex study of propellant, as well as its potential capabilities under given laboratory conditions, was carried out

As a result of processing of the experimental data results obtained using the classical throwing scheme and the-throwing scheme with the TC at an initial charge of  $+20\text{ }^\circ\text{C}$ , the matching parameters were obtained on the basis of a comparison of the experimental and calculated data, with a discrepancy of not more than 0.77%.



The parametric investigation was carried out to determine the possibility of increasing the projectile muzzle velocity in the pressure range not exceeding 600 MPa. Specific values of the variable parameters were obtained at which the muzzle velocity was increased by 14.9% relative to the value obtained in the experiment.

## 5. Conclusion

The results of the study were obtained for the standard laboratory temperature and were used later to investigate throwing at lower (-50 °C) and higher (+ 40 °C) temperatures to determine the temperature coefficients of the propellant. This made it possible to carry out a study on the possibilities of modernization of the throwing using this propellant for different temperatures.

## Acknowledgement

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