

## Mathematical Model of Energy Transformation Processes in Barrel System for Determining Shooting Performance

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### Abstract

A phenomenon has been singled out that is present during almost every shot. It manifests itself in a muzzle blast in the form of soot of a certain amount. The Bell-Boudoir thermochemical reaction has been defined, which explains the formation of soot in powder gases during the shot. The conditions making it possible to manifest have been mentioned. A method for solving the problem of internal ballistics has been developed, enabling to determine the temperature of powder gases along the length of the gun barrel at different times and at different positions of the projectile in the barrel. The modelling of the powder gases temperature distribution in the barrel space between the charging chamber and the moving projectile has been carried out in the model system. The possibility of changing the length of the zone of the Bell-Boudoir reaction (the zone of soot formation) depending on the initial data has been shown. The use of a fresh powder charge and a degraded one has been modelled.

**Keywords:** gun; powder gases; temperature distribution; disproportionation reaction; soot.

### 1. Introduction

The purpose of gunpowder involves their mass use at unpredictable times over a long period. As a result, they accumulate in arsenals with different periods of storage. Nitrocellulose (NC) powders are characterized by instability of the chemical composition during storage. Selective quality control of the batch of NC gunpowder used and the lack of data for its individual parts complicate the fulfilment of the tasks of firing. The scatter in the characteristics of propellant charges within even one batch increases with the expiration of the warranty period for the storage of gunpowder. The technical condition of the barrel and the degree of its wear also affect the accuracy of shooting. This characteristic is variable for various guns, including depending on the number and power of shots fired, on the initial state of the barrel.

The models used to solve the problems of internal ballistics make it possible to calculate a number of parameters of processes of the external manifestation of a shot. One of them, which lends itself well to video recording, is the movement of the projectile. According to a number of features, muzzle blast and ballistic waves can be distinguished. They can serve as a basis for indirect measurement of the projectile velocity for analysing the state of an artillery system [1]–[2]. The least attention is paid to a muzzle flash and how changes in the parameters of internal ballistics processes influence it. But it is the most informative in the external manifestation of the shot and lends itself well to video recording. Thus, to determine the parameters of internal ballistics processes (velocity and pressure), which depend on the state of the propellant charge and the technical condition of the barrel, it is relevant to analyse the

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effects that accompany the external manifestation of the shot. To ensure the possibility of taking them into account, it is necessary to further develop the mathematical model of physico-chemical processes accompanying the shot.

The purpose of the article is to develop a mathematical model and a method for determining the distributed temperature parameters in the powder gases formed in the barrel system in order to identify the modes of soot formation during a shot.

## **2. Analysis of reference data and problem statement**

The mathematical models (hereinafter referred to as MMs) used to determine the parameters of a shot generally mainly differ in the degree of detail in describing these processes. Thus, in its simplest form, it can be a lumped model and a classical analytical [3]–[4] or numerical solution of systems of ordinary differential equations [5]. With the development of numerical methods and the availability of computing resources, distributed models appeared [6], as well as models that take into account the possibility of a two-phase flow of powder gases (hereinafter referred to as PGs) [7]. In the latter case, particles of burning gunpowder are considered as the condensed phase.

A consequence of the complexity of processes accompanying the shot is the limited accuracy of their mathematical formulation. As a result, the models contain empirical coefficients that allow matching the calculated process parameters with the corresponding quantities in experimental studies and practice firing. The above examples of improving the MMs and the methods of their solution made it possible to reduce the influence of empirical coefficients, but did not eliminate it. This allows us to assume not only inaccuracy, but also incompleteness of description of the occurring phenomena. The processes of internal ballistics are difficult to study instrumentally. But their consequences should be reflected in external manifestations, in particular in the nature of formation and flow of muzzle flash. An attempt to use such a relationship is implemented in a number of works. For example, in [8], the main task is to study the PG flow in a muzzle flash in the presence of a muzzle brake compensator. As the initial data for its solution, the results of a numerical solution of the problem of internal ballistics are used, taking into account the chemical kinetics of the burning reactions of gunpowder in the barrel and of PGs in the muzzle flash. The phenomenon of a secondary PG flash was noted. CO and H<sub>2</sub> gases are indicated as the main combustible component.

In the composition of the NC gunpowder, there is not enough oxygen to oxidize, according to the maximum valence, all the chemical elements included in it. The deficit can be ~20%. But when solving the problems of internal ballistics, taking into account the chemical kinetics of the processes of burning of gunpowder, the conditions for possible formation of a condensed phase in the form of soot are not distinguished. Thus, the issues of the causes and the localization (in the barrel or in the muzzle flash) of formation of significant amounts of soot remain unclear.

Specialists who study the problems of determining the type and location of a gun by muzzle flash point to the presence of soot in muzzle blast [10]–[11]. An attempt to use phenomenological data on the muzzle flash composition, temperature, and energy emphasizes the understanding of the importance of such parameters. But significant deviations in the comparison of experimental data and calculation results indicate the absence of appropriate adequate models for their determination.

There is also no explanation in the description of some processes occurring in a muzzle flash. Thus, in [8], the secondary flash is explained by the ignition of PG components in the air in the form of CO and H<sub>2</sub>. Muzzle blast is considered as the reason for additional heating of the mixture. This effect is known [12] as a result of range field tests.

In a number of works [13]–[14], the influence of barrel wear and gunpowder degradation on the parameters of the shot process is studied. The results are obtained by numerical studies based on known models. At the same time, the completeness of accounting in the used models of phenomena in the process of a shot is practically not considered. There is no comparison of the obtained results with the effects in the external manifestation of the shot. Thus, in [13], only the shape of the hole in the target is considered. Its elliptical shape is explained by an increase in the angle of attack of the projectile due to a decrease in the speed of its rotation with barrel wear. But in practical cases, the speed of rotation of the projectile can be reduced even at a lower speed of the projectile at the exit from the barrel due to the degradation of gunpowder. In [14], the process parameters calculated taking into account barrel wear and gunpowder degradation are not linked to the effects of the external manifestation of the shot, which can be controlled.

### 3. Purpose and objectives of research

To achieve the purpose, the following objectives are formulated:

- To analyse the reasons for the formation of soot in the bore during a shot.
- To develop, on the basis of physical and chemical processes of expansion of powder gases in the bore, a mathematical model that determines the conditions for the formation of soot.
- To develop a method for determining the change in the temperature of powder gases along the length of the barrel during the shot.
- To model the temperature distribution in the space of the barrel between the charging chamber and the moving projectile.

### 4. Model and method for determining the temperature of powder gases along the length of the barrel

#### 4.1. Analysis of the causes of soot formation in the bore during firing

The effects of intermediate ballistics (muzzle blast, muzzle flash) depend on the processes of internal ballistics. Their feature is the possibility of visual observation. In the works noted above, the composition of the PGs along the length of the barrel is assumed to be constant and is determined based on the burning process of the NC gunpowder of a certain brand. Its main components:  $CO_2$ ,  $H_2O$ ,  $N_2$ —inert,  $CO$ ,  $H_2$ ,  $CH_4$ —combustible. All components are gaseous.

Such geometry of the muzzle blast during its flash can also be explained by the presence of soot in the ogival head. An increase in temperature during a muzzle flash leads to an increase in the volume of PG in all parts of the muzzle blast. But during the burning of soot, the molar amount of gaseous products does not change before and after the reaction:



At the same time, during the burning of  $CO$  and  $H_2$ , the molar amount of gaseous reaction products decreases by 1.5 times compared to the initial value:



This can reduce the degree of expansion of the PG due to heating in the root of the muzzle blast (in the soot-free zone) during the muzzle flash.

Thus, the analysis of the type of muzzle blast and muzzle flash shows that the composition of the PG along the length of the barrel at the moment of the projectile leaving it has a variable composition. Soot may be part of the PG.

When fired, NC gunpowder does not imply the formation of soot during its burning. Its presence in the muzzle blast indicates the possibility of an additional chemical reaction.

The amount of oxygen in the composition of the NC gunpowder is not enough to oxidize all combustible elements to the maximum valency. The combination of the presence of carbon monoxide  $CO$  and a sharp decrease in the temperature of the PG mixture to quantities less than 1,300–1,400K creates the condition for the possibility of the Bell-Boudoir reaction:



The presence of this reaction affects the value of the PG parameters.

#### 4.2. Model of soot formation based on the Bell-Boudoir reaction in the problem of internal ballistics

Reaction (3) is reversible. But in practice, under the name of the Bell-Boudoir reaction, it is most often considered in one direction with a mention of the possibility of its reversibility:



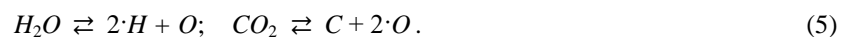
Processes with a reaction proceeding in the direction (3) are considered less frequently. These include, for example, the technology for removing  $CO$  from a hydrogen-rich stream for use in low-temperature fuel cells [15]. Another example of consideration of  $CO$  disproportionation can be the study of catalyst poisoning during the synthesis of methanol (methyl alcohol) from synthesis gas [16].

The thermodynamic equilibrium of the Bell-Boudoir reaction at a temperature of  $\sim 1,300$  K is almost completely shifted towards the formation of carbon monoxide (4). Moreover, at this temperature, reaction (3) remains exothermic. This situation is explained by the *endergonic* nature of reaction (3) at high temperature, which favours the *exergonic* reaction (4). At 400 K, the thermodynamic equilibrium is completely shifted towards the formation of carbon dioxide (3). But in practice, carbon monoxide ( $CO$ ) remains in a stable state at this temperature, which is explained by the low rate of reaction (3) under normal conditions.

Based on the results of [17], the temperature range of 1,000–1,200 K can be singled out as the most favourable for the formation of carbon in accordance with reaction (3). On the one hand, in this temperature range, the thermodynamic equilibrium still allows the reaction to proceed. Under the conditions of a shot, before the projectile exits the barrel, the PG pressure can be equal to  $\sim 30$ – $50$  MPa. The reaction rate can be even higher if the PG temperature drops to  $\sim 1,200$ – $1,300$  K when the projectile accelerates in the barrel until it reaches the muzzle face. In this case, the PG pressure will be higher, and the rate of reaction (3) will increase. This explains the formation of a large amount of soot during the shot, which is supported by the results of work [18].

As the projectile moves along the bore, the quantity of the PG pressure can reach values of  $\sim 300$ – $500$  MPa. Such pressure, as well as high temperature, determines the equilibrium (or close to it) state of chemical reactions between PG components. Determination of the PG composition is based on the solution of a system that includes the equations of the law of mass action, the law of conservation of matter, and Dalton law.

A distinctive feature is the form of equations of the law of mass action. The equations for the formation of possible PG components from elementary chemicals are used as a basis for their recording. Example:

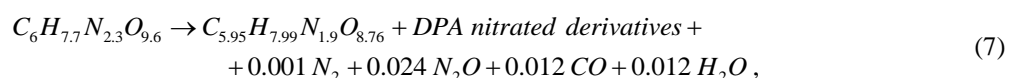


This form of recording is universal. It allows obtaining a closed system of equations based on a list of substances that may be present in the mixture. In the accepted models that describe the firing process, the composition of PG for NC gunpowder is determined based on the following list of its components:



To reflect the possibility of soot formation, we will supplement this list with one more component and designate it with  $F_C$  (free carbon) symbol, finely dispersed condensed phase of carbon. The method for calculating the thermodynamic parameters of a mixture of gaseous products during the formation of a condensed phase is given in [19].

To calculate the composition of PG, we need data on the composition of the powder charge. They can be considered known after its manufacture and during the storage life. In the future, due to destructive changes, the composition may change significantly. Based on the data of [20], the process of degradation of plastic high explosives can be reflected as follows:



where DPA is diphenylamine.

As the projectile moves along the barrel, the PG temperature continuously changes and, as a result, the ratio of their components changes. A peculiar feature is the constancy of the gross formula of the gas mixture and its equality to the original gross formula of the powder charge. This makes it possible to calculate at a preliminary stage the PG composition for various temperatures and approximate it using, for example, a polynomial dependence. In the future, this dependence can be used in solving problems of internal ballistics at various degrees of degradation of the initial charge.

For further modelling, we will choose a sample of gunpowder, the initial composition of which is given in [21], its gross formula is as follows:



or, bringing it to the form of (7):



When describing the properties of gun powders, it is customary to use their force ( $f$ ) as an energy characteristic. At the same time, in [19], the calculation is based on the enthalpy of formation of the initial substance. Let's estimate the ratio of these quantities. Let's assume that: the combustion process is isoenthalpic (constant-enthalpy process), and the gas-phase process is adiabatic. According to the assumptions made:

$$I_{se}^{GP} = I_{se}^{PG} = \frac{\gamma}{\gamma-1} \cdot f, \quad (10)$$

where  $I_{se}^{GP}$  is the specific gunpowder enthalpy,  $I_{se}^{PG}$  is the specific powder gases enthalpy,  $\gamma$  is the adiabatic index, and  $f$  is the force of gunpowder.

The molar equilibrium composition of PGs was determined at different temperatures. The results are given in Table 1 below.

Table 1. Molar composition of PGs at different temperatures

Composition of PGs	Temperature, K							
	2,940	2,000	1,500	1,400	1,300	1,200	1,100	1,000
<i>CO</i>	0.400	0.396	0.392	0.377	0.362	0.333	0.273	0.177
<i>CO<sub>2</sub></i>	0.125	0.129	0.133	0.146	0.159	0.180	0.220	0.279
<i>H<sub>2</sub>O</i>	0.167	0.165	0.163	0.158	0.152	0.152	0.167	0.212
<i>H<sub>2</sub></i>	0.211	0.213	0.215	0.221	0.229	0.236	0.236	0.219
<i>N<sub>2</sub></i>	0.097	0.097	0.097	0.097	0.098	0.100	0.104	0.112
<i>CH<sub>4</sub></i>	0	0	0	0	0	0	0.0003	0.0015
<i>F<sub>C</sub></i>	0	0	0.0016	0.0036	0.0092	0.0253	0.0673	0.1474

The ideal gas approximation was used in the modelling. The ratio of the amount of *CO<sub>2</sub>*, *CO*, *F<sub>C</sub>* in the temperature range from 1,000 K to 1,500 K corresponds to the data of [15]–[16].

#### 4.3. Method for determining the PG temperature along the length of the barrel during the shot for a distributed parameter model

To solve the problem of internal ballistics, first of all, the values of the quantities that determine the gas-dynamic processes (pressures and temperatures) taking place in the PGs along the length of the barrel at each moment during the shot are averaged. This procedure simplifies the solution.

Thus, in [22], the calculations were made for a 100 mm calibre gun, which has a charging chamber with a length of  $l_c = 1$  m and a barrel length of  $L_d = 5$  m. In general, in publicly available literary sources, no information was found on the PG temperature distribution along the length of the barrel during the movement of the projectile along the barrel. When using models that do not take into account the possibility of the formation of a condensed phase, there is no need for such information. It is believed that in the process of firing in the range of PG temperature changes, the composition of PGs remains practically unchanged. This is also confirmed by the calculation results given in Table 1. In the range from the burning temperature (2,940 K) to the temperature of the beginning of formation of a significant amount of soot ( $\sim 1,400$  K), the PG composition remains practically unchanged.

To be able to consider the PG temperature distribution along the bore, the mathematical model (MM) of the process must be written in partial derivatives. This, as a rule, leads to the need to use numerical methods to solve it. For a preliminary assessment of the temperature distribution under the assumptions made, this approach is not rational. The following approach is proposed to describe the firing process:

- The movement of the projectile along the bore in simplified form is divided into two parts: during and after the burning of gunpowder.
- The powder charge burns in discretely of equal mass.
- The pressure at which the next discrete of the charge is burned is considered constant and is taken to be equal to the pressure after the end of the PG expansion at the previous step of the calculation. This pressure quantity determines the combustion time of the next fraction of the charge ( $t_i$ ). It is the timing interval for the next step. Depending on the current pressure, the combustion time interval for the next fraction of the charge and, accordingly, the timing interval for the next step will be variable.
- The next portion of PGs with  $m_i$  mass is formed without influencing the already existing PGs (for example, outside the bore). This step corresponds to the assumption of not taking into account the volume of the powder charge and, therefore, not taking into account the change in the space behind the shot as the powder burns.
- The next generated portion of PGs enters the charging chamber instantly through its end surface (Fig. 1). An instantaneous increase in PG pressure occurs, and its new quantity ( $p_i$ ) is formed, determined by the amount of added PGs, as well as by the volume ( $w_0, w_1, \dots, w_{i-2}, w_{i-1}$ ) and pressure of already existing PGs; during  $t_i$  time interval (the duration of the next calculation step), the PG expands, and the projectile accelerates. At the end of the time interval under consideration, the quantity of the PG pressure is formed, which is used to determine the burning time of the next fraction of the powder charge at the next time step of time calculation.
- After combustion of the powder charge, the calculation of the expansion of PGs and the acceleration of the shot before it leaves the barrel is carried out.



Fig. 1. Scheme of forming the incoming PG fraction at the next calculation step.

At this stage, the distribution of the PG temperature along the barrel is modelled during the firing. In the calculated dependencies, the average values of some quantities are used, corresponding to modern barrelled systems.

In accordance with the accepted assumptions, a solution method is suggested for a mathematical model.

Step 1. The PG temperature is determined from (10); the amount of powder charge required for the formation of the shot-start pressure in the charging chamber is determined from the equation of state. The quantity of the shot-start pressure, the volume of the charging chamber (excluding the charge volume), and the adiabatic index are given. In accordance with the part of the burnt charge, the enthalpy of the considered PG volume is determined. The remaining mass of the powder charge is determined, and the number of calculation

steps is selected. The mass of the charge part ( $m_i$ ), the combustion of which is considered at one calculation step, is determined. The masses of all parts are the same. The shot-start pressure is the initial pressure for the next calculation step and determines the burning rate of a part of the powder charge. Later on, this PG volume is denoted as  $w_0$  (Fig. 1).

Step 2. Using the final pressure from step 1 of the calculation, burning time  $t_i$  of part  $m_i$  of the powder charge is determined. Linear burning law  $u_1=u_0 \cdot p$  and constant burning area  $F$  are taken. In accordance with this:

$$m_i = (u_0 \cdot p) \cdot F \cdot t_i \Rightarrow t_i = \frac{m_i}{(u_0 \cdot F) \cdot p}. \quad (11)$$

The way in which the bracketed expression is defined is described below.

Step 3. The formed part of PGs enters (instantly) into the space behind the shot without changing its volume. In accordance with the current  $i$ -th number of the calculation step, this part of PGs will henceforth be denoted as  $w_i$ . The PGs enthalpy ( $I_i^n$ ) is calculated as the sum of their enthalpy from the end of the previous calculation step that is introduced with the current fraction. In accordance with

$$I_i^n = \frac{\gamma}{\gamma-1} \cdot P_i^n \cdot W_i^n \Rightarrow P_i^n = \frac{\gamma-1}{\gamma} \cdot \frac{I_i^n}{W_i^n}. \quad (12)$$

The PG mixture pressure ( $P_i^n$ ) is determined at the beginning of the calculation step. Taking into account the assumption that PG volumes from the corresponding calculation steps are not mixed, their new quantities are determined.

Step 4. The expansion of PGs and the acceleration of the shot at the current calculation step occurs during the  $t_i$  time determined at step 2 and is described by the following ratio:

$$\varphi M \frac{d^2 x}{dt^2} = P \cdot S, \quad (13)$$

where  $M$  is the mass of the projectile,  $\varphi$  is the coefficient that takes into account the fictitious quantity of the projectile mass,  $x$  is the length of the space behind the shot of the barrel,  $P$  is the PG pressure, and  $S$  is the cross-sectional area of the barrel.

$P$  quantity is determined from the formula describing the adiabatic process of gas expansion:

$$(P_i^n) \cdot (W_i^n)^\gamma = (P_i) \cdot (W_i)^\gamma \Rightarrow P_i = (P_i^n) \cdot \left( \frac{W_i^n}{W_i} \right)^\gamma, \quad (14)$$

where  $P_i^n$ ,  $W_i^n$  are the quantities of pressure and volume of the space behind the shot at the initial moment at the calculation step (corresponding quantities at the end of the previous calculation step),  $P_i$ ,  $W_i$  are the quantities of pressure and volume at the current moment of calculation.

Taking into account  $W_i=S \cdot x_i$  and (14), the expression (13) will be written as follows:

$$\frac{d^2 x}{dt^2} - \frac{r}{(x)^\gamma} = 0, \quad r = \frac{P_i^n \cdot S \cdot (x_i^n)^\gamma}{\varphi \cdot M}, \quad (15)$$

where  $x_i^n$  is the length of the space behind the shot at the initial moment of the calculation step.

Let's linearize the second term of equation (15) at point  $x_i^n$ . We use as initial conditions the values of  $x_i^n$  quantities and projectile velocity  $v_i^n$  at the initial time of calculation at the current step (final velocity at the previous calculation step). Assuming, as before, that  $\gamma=1.2$ , solution (15) can be written as follows:

$$x(t) = \frac{v^n}{\sqrt{d_1}} \sin(\sqrt{d_1} \cdot t) - \frac{5}{6} x_i^n \cos(\sqrt{d_1} \cdot t) + \frac{11}{6} x_i^n, \quad \text{where } d_1 = \frac{6r}{5x_i^n}. \quad (16)$$

By substituting value  $t_i$  into this expression, the value of the projectile space behind the shot  $x_i^k$  is determined by the end of the current calculation step, and from the derivative of (16)

$$v = x'(t) = v^n \cos(\sqrt{d_1} \cdot t) + \frac{5}{6} x_i^n \sqrt{d_1} \sin(\sqrt{d_1} \cdot t) \quad (17)$$

projectile velocity  $v_i^k$  at the moment.

Step 5. For the accepted assumptions from the first law of thermodynamics

$$\Delta U = A, \quad (18)$$

taking into account the PG adiabatic expansion and, accordingly,  $I = \gamma \cdot U$ , from (18) by the end of the current calculation step, it follows that:

$$I_{res} = I_{com} - \gamma \cdot \phi M \frac{(v_i^k)^2}{2}. \quad (19)$$

where  $\Delta U$  is the internal energy of PGs spent on work  $A$  to accelerate the shot with fictitious mass  $\phi M$ ,  $I_{com}$  is total enthalpy introduced from the PGs in the space behind the shot,  $I_{res}$  is the residual enthalpy at the end of the current calculation step after the work on acceleration of the shot has been completed. Equation (19) can be regarded as a simplified analogue in the enthalpic form of the Résal equation. From (20) correlation, the PG pressure is determined at the end of the calculation step.

$$I_{res} = \frac{\gamma}{\gamma-1} \cdot P_i^k \cdot W_i^k \Rightarrow P_i^k = \frac{\gamma-1}{\gamma} \cdot \frac{I_{res}}{W_i^k} \quad (20)$$

Step 6. If not all the powder charge has been used by the beginning of the next calculation step, go to Step 2.

Step 7. The calculation is carried out in accordance with the method described in paragraphs 2–5, but without taking into account the entry of PGs into the space behind the shot. The end time of the calculation is determined by the moment the shot reaches the muzzle face.

#### 4.4 Modelling results of the temperature distribution in the space of the barrel between the charging chamber and the moving projectile

It was determined that when burning 0.5 kg of charge with a motionless projectile, a pressure of  $\sim 3.06 \cdot 10^7$  Pa will be reached, close to the assumed shot-start pressure. The process of burning the remaining 10.5 kg of charge is divided into 35 steps of  $\Delta m = m_i = 0.3$  kg. By selecting the value of the expression in brackets in (11), values  $\tilde{V} = 633.5$  m/s and  $V = 774.5$  m/s were obtained. At the same time,  $u_0 \cdot F = 8.65 \cdot 10^{-8}$  m<sup>3</sup>/s was assumed. Having obtained in the process of calculation the values of the reference values close to the given ones, it can be assumed that the calculated PG temperature distribution in the space behind the shot adequately reflects the actual course of the process.

Fig. 2,a shows the change in pressure, and (Fig. 2,b) shows the temperature distribution in the space behind the shot at different positions of the projectile.

The pressure quantity in Fig. 2, a is displayed for a point tied to the projectile base. This explains the position of the beginning of the graph. Along the abscissa axis, it is determined by the length of the charging chamber. Along the y-axis, it is determined by the quantity of the shot-start pressure. In Fig. 2,b, the temperature values are displayed for the points associated with the corresponding PG parts. All parts have the same mass (in this case, 0.3 kg each). But at different pressures, they have different lengths. For this reason, the coordinates of the beginnings of graphs 1, 2, 3 in Fig. 2,b along the abscissa axis do not match.



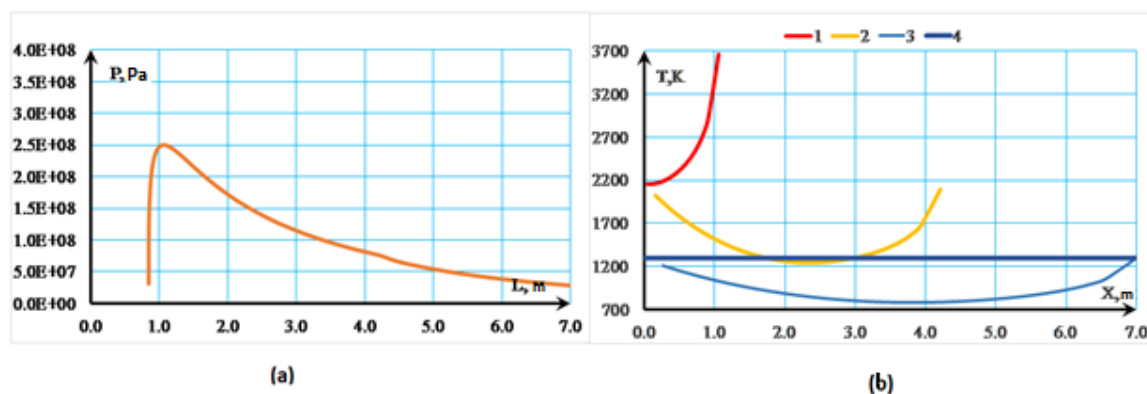


Fig. 2. The results of calculating the pressure (a) and temperature (b) of PGs for a reduced charge of fresh powder: a – pressure change in the space behind the shot; b – PG temperature distribution at different projectile positions: 1 – at the moment of maximum pressure in the space behind the shot; 2 – at the end of burning of the powder charge; 3 – when the projectile is at the muzzle face; 4 – temperature limit of the Bell-Boudoir reaction.

The calculation results show that until the end of burning of the powder charge (Fig. 2,b: graphs 1, 2), there are no conditions for the Bell-Boudoir reaction to proceed. The PG temperature throughout the space behind the shot is above the boundary of its beginning (Fig. 2,b: graph 4). But at the stage of PG expansion after the end of charge burning (Fig. 2,b: graph 3), there are conditions for the formation of a condensed phase in the form of soot. In this case, when the projectile moves along the muzzle face, the highest temperatures are observed at the base of the projectile and the base of the charging chamber. In the middle part of the PGs, their temperature is below the boundary of the carbon monoxide disproportionation reaction for the longest period of time.

To assess the effect of the degree of degradation of the powder charge on the value of the shot parameters, a calculation was made for gunpowder with the same gross formula (8) with a decrease in its energy capacity by 8%. For specific enthalpy  $I=5,240$  J/kg and data on the shot parameter of the model artillery system and the reference values of the system quantities, the results shown in Fig. 3 have been obtained. The designations similar to Fig. 2 have been used.

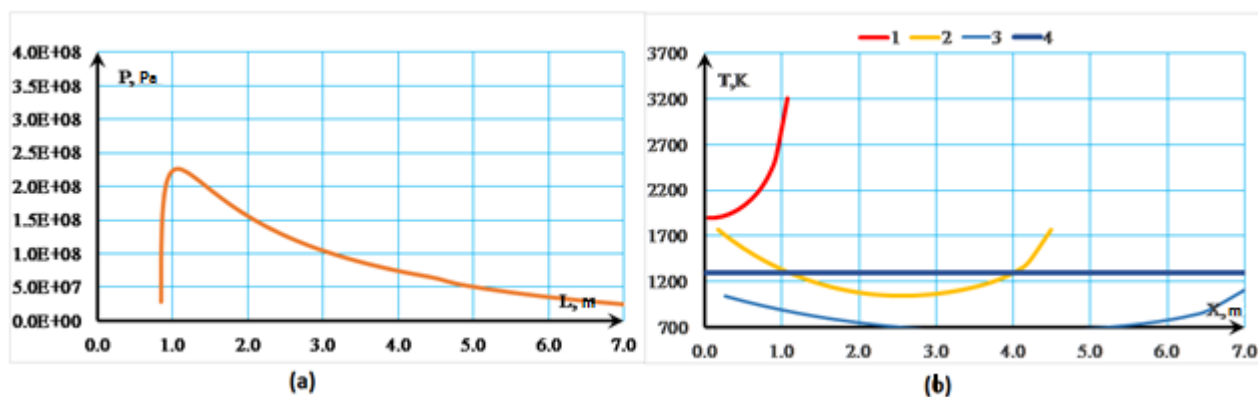


Fig. 3. The results of calculating the PG pressure (a) and temperature (b) for a reduced charge of degraded gunpowder.

As a result, the characteristic velocities are determined as  $\tilde{V}=618.5$  m/s and  $V=750$  m/s. In relation to the previously calculated corresponding values for fresh powder, they differ by no more than 2.5% – 3.5%. The nature of change in the PG temperature profile has remained similar to Fig. 2,b. But temperatures have undergone significant changes. In the case under consideration, the temperatures of most of the PGs are for most of the time below the boundary that determines the possibility of the Bell-Boudoir reaction. This increases the likelihood of formation of a condensed phase (of carbon).

To estimate the range of PG temperature change at different charge values, a calculation was made for fresh gunpowder mass  $m=18.4$  kg (full charge). The calculation results are shown in Fig. 4. The designations similar to Fig. 2 have been used.

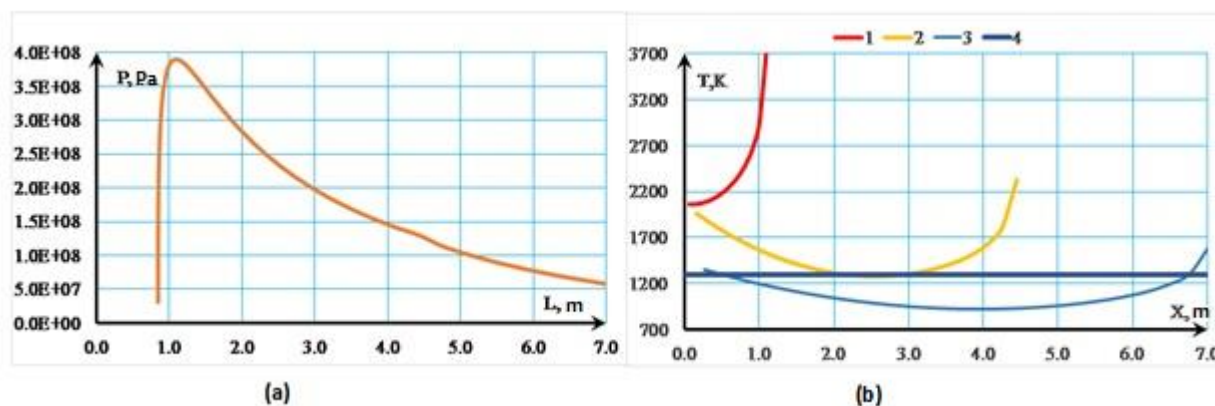


Fig. 4. The results of calculating PG pressure (a) and temperature (b) for a full charge of fresh powder ( $m=18.4$  kg).

The reference velocities for the case under consideration are  $V=945$  m/s and  $\tilde{V}=756$  m/s. As a result of the calculation, values  $V=944$  m/s and  $\tilde{V}=780$  m/s were obtained. A feature of the obtained results is the excess of the PG temperature at the base of the charging chamber and the muzzle face of the boundary temperature for the Bell-Boudoir reaction. In other words, the soot component should be absent in the initial and final parts of the muzzle blast.

### 5. Discussion of calculation results. Determination of conflagration site and shape of muzzle flash

The proposed model of internal ballistics processes is built using significant assumptions and is used for evaluation calculations. Nevertheless, the results obtained can serve as a basis for revealing the relationship between the parameters of the PG expansion process in the barrel and the nature of the muzzle flash.

The place of initiation of the muzzle flash can be explained on the basis of the type of profile of the PG temperature change along the length of the barrel. This is their maximum temperature in the area of the charging chamber and the muzzle face. In addition, the flash point of  $H_2$  ( $\sim 800$  K) and  $CO$  ( $\sim 900$  K) should be taken into account. The calculation results indicate the possibility of reducing the PG temperature below these limits. Their temperature continues to decrease even after exiting the barrel.

The examples given reflect the many-valued relationship between the parameters of the internal ballistics processes of a shot and its external manifestations in the form of muzzle blast and muzzle flash. In turn, the parameters of the internal ballistics of the shot are influenced by the state of the powder charge (the degree of its degradation) and the technical condition of the barrel (its wear). Thus, on the basis of the proposed model, a method for determining the state of the artillery system in real time during the firing process can be built. A similar approach was used in solving a model problem [24].

### 6. Conclusion

The reason for the impossibility of describing the phenomenon of soot formation using existing models of internal ballistics processes has been determined. It is based on the lack of consideration of the PG temperature distribution along the length of the barrel and its change during the shot. A model has been proposed that allows estimating such changes in PG temperature.

Based on the proposed model, an algorithm for solving the problem of internal ballistics has been developed with the possibility of determining the PG temperature along the length of the barrel at different times and at different positions of the projectile in the barrel. The initial model has been built using significant assumptions. The results obtained on its basis can only be estimative. Because of this, the algorithm is based on simple calculations, without the involvement of high-power computing hardware.

The modelling of the PG temperature distribution in the barrel space between the charging chamber and the moving projectile has been carried out in the model system. The possibility of changing the length of the zone of the

Bell-Boudoir reaction (the zone of soot formation) depending on the initial data has been shown. The use of a fresh powder charge and a degraded one has been modelled. Full and reduced charges have been considered. The modelling results have showed the reason for the possibility of initiating a secondary flash of muzzle blast both from its frontal side and from the side of the muzzle brake.

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## **Математична модель процесів перетворення енергії у системі ствола для визначення показників стрільби**

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### **Анотація**

Виділено явище, присутнє майже при кожному пострілі. Воно проявляється в дульному викиді у вигляді деякого об'єму сажі. Визначена термохімічна реакція Будуара-Белла, що пояснює утворення сажі в порохових газах в процесі пострілу. Виділені умови можливості її прояву. Розроблено метод розв'язання задачі внутрішньої балістики з можливістю визначення температури порохових газів по довжині ствола гармати в різні моменти часу і при різному положенні снаряда в стволі. Проведено моделювання розподілу температури порохових газів в просторі ствола гармати між зарядною коморою і снарядом, що рухається, в модельній системі. Показана можливість зміни протяжності зони протікання реакції Будуара-Белла (зони утворення сажі) залежно від початкових даних. Моделювалося використання свіжого порохового заряду і заряду, що деградував.

**Ключові слова:** гармата; порохові гази; розподіл температури; реакція диспропорціонування; сажа; дульний спалах.