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Determining the Parameters of the Combustion Law of the Travelling Charge Propellant in 30-mm Ballistic Installation Shot

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Abstract. Recently, more and more researchers have shown interest in studying the temperature gradient of unconventional shots, including shots with a travelling charge. The paper considers the possibility of taking into account the effect of the initial charge temperature, in particular, on the travelling charge from the pasty propellant, in the form of a linear relationship, through the use of a mathematical tool for qualitative analysis of experimental data. A study was made of taking into account the influence of the temperature coefficient in one or several parameters characterizing the propellant combustion on the ballistic characteristics of the shot. It is shown that for pasty propellants, taking into account the temperature coefficient in the travelling charge dispersion rate and the layer-by-layer burning rate of dispersed propellant particles, as well as the dependence of the transition pulse to the accelerated TC burning mode on the initial charge temperature, provides good agreement on the shapes of pressure variation curves in the loading chamber and velocity projectile in the barrel.

INTRODUCTION

An analysis of the publications shows that recently there has been a great interest of researchers to the question of the initial charge temperature influence on the ballistic characteristics of the shot, especially for non-traditional throwing schemes. Maintaining the throwing velocity in the entire operating temperature range is the main factor ensuring effective penetration into composite and spaced shields, behind-shield defeat of control units, initiation of explosives, etc.

The prospect of using travelling charges (TC) from pasty propellants (PP) for the barrel-reactive artillery system is largely determined by the composition ability to maintain or slightly change the ballistic parameters of the shot in a wide range of initial temperatures. Recently, more and more researchers have shown interest in studying the temperature gradient of unconventional shots, including shots with TC [1 – 8]. Researchers from the Research Institute of AMM at Tomsk State University showed the possibility of using these propellants with a change in the initial charge temperature from - 50 to + 50 °C and found its noticeable effect on the ballistic indicators of shots from the TC [9, 10]. The paper investigates the possibility of using temperature coefficients of the propellant combustion law, determined under conditions of manometric tests, for calculating the ballistic parameters of a shot from a model ballistic installation.

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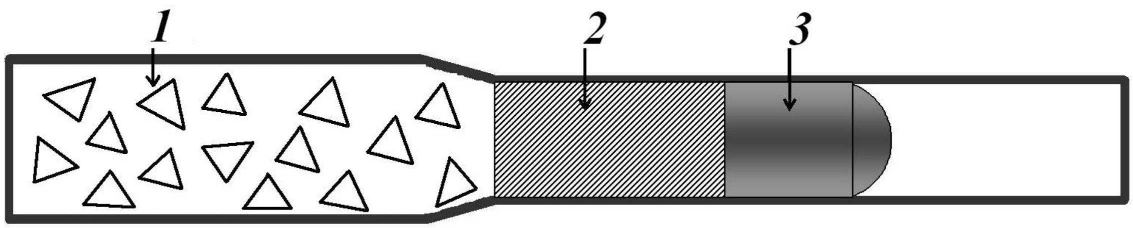
LOADING SCHEME WITH TRAVVELING CHARGE

Among non-traditional throwing schemes, the most common is the shot with TC located behind the projectile, which allows to solve the problem of "saturation effect" arising by using the classical loading scheme. This loading scheme allows you to redistribute energy in the space behind the projectile and increase the muzzle velocity of the projectile. Figure 1 shows the main components of the used shot scheme. At the moment, the actual problem is the effect of the initial charge temperature on the ballistic characteristics of a shot with the TC, which is currently little studied. Analyzing the ballistic characteristics of the shot, it should be noted that in the TC shot scheme the classical relationship between the maximum pressure and the muzzle velocity of the projectile does not hold, so the main attention should be paid to the dependence of the muzzle projectile velocity on the initial charge temperature.



1 – traditional gunpowder charge; 2 – travelling charge; 3 – projected element

FIGURE 1. General scheme of throwing with TC

Figure 2 shows the characteristic experimental dependences of the pressure in the loading chamber on time $P(t)$ (a) and the calculated dependences of the pressure at the projectile bottom on the path traveled along the bore channel (b) in gunpowder charge and with TC shots. The point on the curve marked the moment of departure of the projectile from the barrel. This graph shows an example in which the TC operation begins immediately after the maximum pressure in the loading chamber. It is seen that the increase in pressure on the descent of the pressure curve (Fig. 2 (a)), characterized by an increase in pressure behind the projectile, the maximum pressure in the shot with the TC is not higher than the shot with the powder charge. At the projectile movement beginning (first 30 cm), the level of maximum pressure at the bottom of the projectile is lower than in the classic shot, and then higher until the projectile leaves the barrel (Fig. 2 (b)).

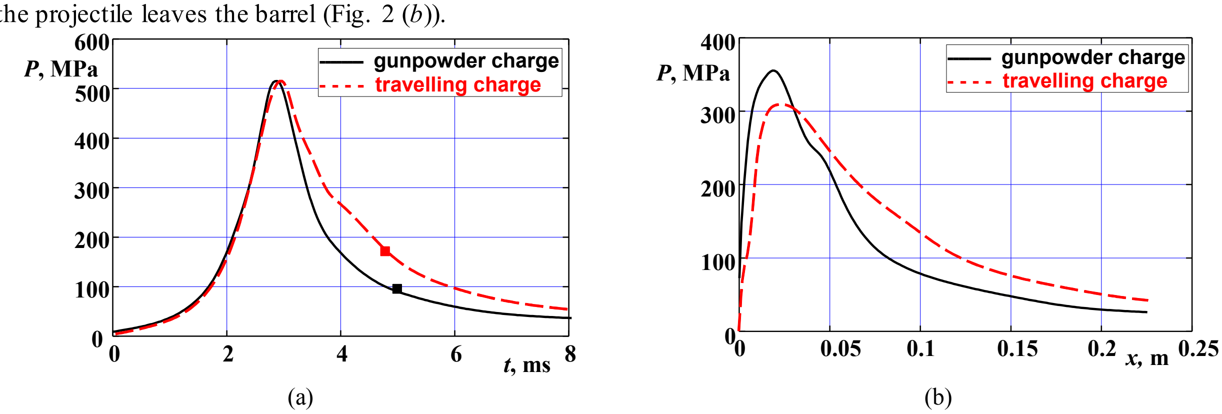


FIGURE 2. The pressure in the loading chamber vs time (a) and the pressure on the projectile vs the path passed through the barrel bore (b)

PASTE PROPELLANT COMBUSTION LAW

The main requirement applied to the propellants used as TC is a high layer-by-layer burning rate from 50 to 250 m/s, which allows them to burn as the projectile moves along the barrel. The law of combustion of propellants can be determined in static (manometric tests) and dynamic (shot) conditions.

To clarify the law of combustion of PP in the conditions of the shot at different initial charge temperatures (T_0), the mathematical model described in [11] was used. It was believed that the powder charge in the chamber instantly ignites and burns at a known rate, the influence of the initial temperature was determined by the tabular coefficients β and θ, which are specified by the manufacturers of the powders. TC ignites some time after the beginning of the combustion of the powder charge in the chamber [12]. The moment of ignition is set by the ignition delay impulse $I = I_{d1}$.

$$I = \int_0^t P dt \tag{1}$$

When TC burning, it is believed that unburned particles and gaseous products of combustion are emitted from the front. The burning of the TC, as a rule, is characterized by two periods - slow with velocity

$$u_1 = B_{s1} P^{\nu_{s1}} \tag{2}$$

and accelerated burning mode

$$u_2 = B_{s2} P^{\nu_{s2}} \tag{3}$$

here u_i is burning rate, B_i is rate factor, P is pressure, ν_i, is exponential coefficient.

The moment of transition between the stages is determined by the achievement by impulse I of the value of the pulse of transition to the accelerated combustion mode $I = I_{di}$. In some calculations, it was believed that propellant particles dispersed from the combustion front of a TC characterized by an initial degree of particle conversion of Ψ_0. The rate of layer-by-layer burning of particles was determined by the formula

$$U_c = B_c P^{\nu_c} \tag{4}$$

here B_c is rate factor, ν_c is exponential coefficient.

In the calculations, the geometrical parameters of the dispersed particles were also determined: an initial thickness of the burning dome, an initial burning surface; an initial volume.

At T_0 = 20 °C, the combustion law parameters ψ_0, ν_s, B_{s1}, B_{s2}, I_{d1}, I_{d2}, B_c, ν_c were defined as the matching parameters of the calculated and experimental data. Solving the direct problem of internal ballistics, that is the parameters changed in a certain range to achieve the maximum possible agreement between the experimental and calculated values of the $P(t)$ and the projectile velocity in the barrel $V_C(t)$ curves, as well as the approximation of the calculated and experimental maximum pressure values muzzle projectile velocity.

According to the results of manometric tests by the PP developer, the values of the temperature coefficient of the layer-by-layer burning rate β_t and the temperature coefficient of ignition delay ε_t were obtained. It was believed that the magnitude of the propellant force does not change with a change in T_0.

Based on the analysis of experimental data in ballistic experiments, the possibility of using β_t to take into account the influence of the initial propellant temperature in the mathematical model by solving the direct problem of internal ballistics was considered. For propellant grade PP-1 coefficient β_t is equal 0.0061 °C. It was assumed that the parameters Ψ_0, ν_s, ν_c do not depend on T_0. Depending on using the β_t coefficient, the study was divided into four stages.

At the first stage, β_t was used depending on the rate of layer-by-layer burning of the TC in the end mode. At the same time, the pasty propellant was completely transformed into combustion products at the front and no dispersed particles were formed (ψ_0 = 1.0).

At the second stage, β_t was used in the dependence of the layer-by-layer burning rate of propellant particles dispersed from the TC burning front at ψ_0 = 0.2, the rate of charge dispersion did not depend on temperature. It also investigated the effect of the size and shape of the propellant particles dispersed from the TC burning front on the ballistic parameters of the shot.

At the third stage, β_t was simultaneously used both as a function of the dispersion rate of the TC, and as a function of the rate of layer-by-layer burning of propellant particles dispersed from the burning front of the TC.

At the fourth stage, along with taking into account the temperature dependence of the rate of dispersion and the rate of layer-by-layer burning of particles, the dependence of the TC I_{d1} combustion mode change pulse on the initial charge temperature was taken into account by applying the coefficient ε_t.

RESULTS AND DISCUSSION

Table shows the results of the computational research, taking into account the effect of the temperature coefficient β_t. A comparison of the calculated and experimental data obtained in experiments using TC from PP-1 propellant in the range of initial charge temperatures from -50 to +50 °C is considered. The law of combustion of the corresponding type (number) was obtained by substituting the calculated coefficients into formulas (1) – (4).

The results of the first stage of calculations, obtained using the end model of the TC combustion, are presented in table (law **1**). Figure 3 (a) presents the reconciliation of the calculated and experimental data. As a result of the matching, the values of the coefficients B_{s1} and B_{s2} were obtained at the initial charge temperature + 20 °C. Then the coefficients B_{s1} and B_{s2} were calculated for the initial charge temperatures T_0 = –50, T_0 = – 30 and T_0 = +50 °C using the formula

$$B_{si}(T_0) = B_{si}(20\ °C)\ [1 + \beta_t\ (T_0 - 20)] \quad (5)$$

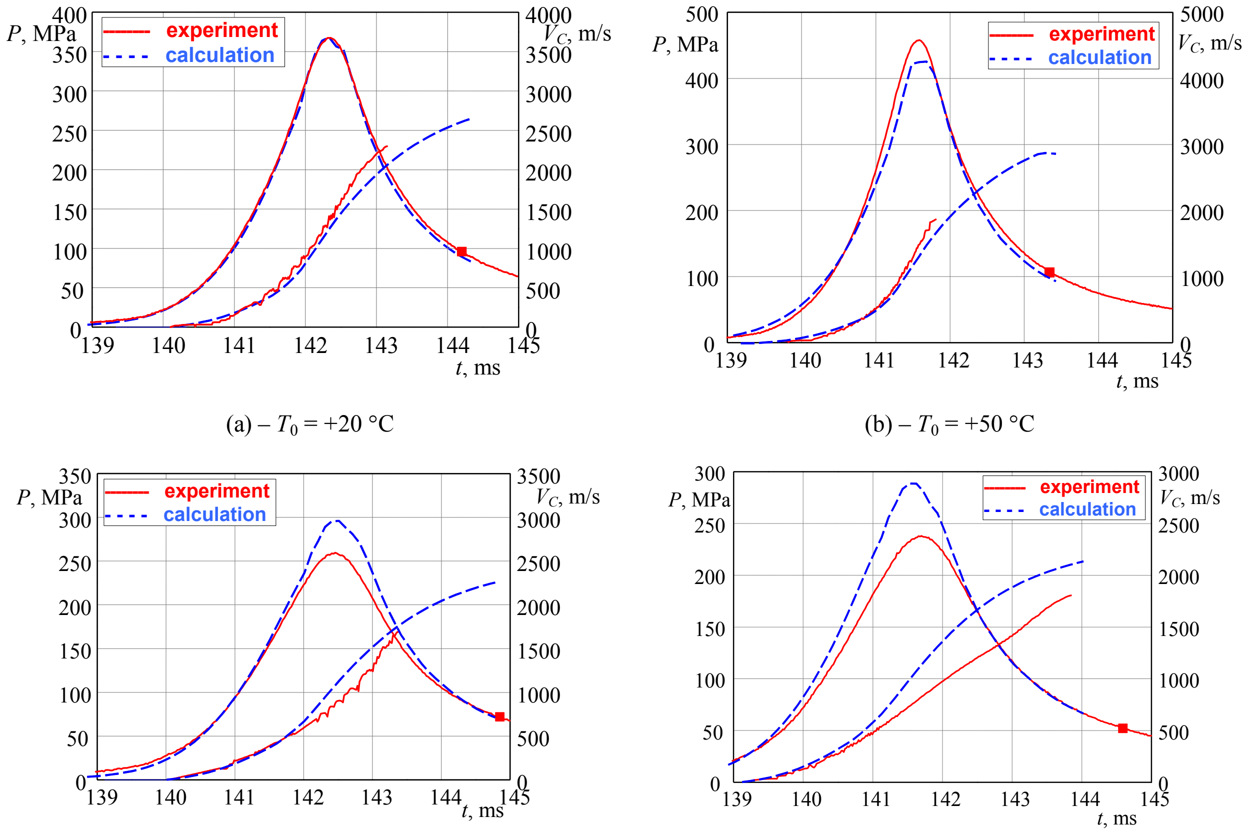
here B_{si}(20 °C) is determined at a temperature (20 °C).

TABLE – The results of applying the laws of dispersion and combustion of TC from high-energy propellant PP-1, taking into account the temperature coefficient β_t

Law type	TC dispersion rate							Final combustion rate			T, °C	ΔP_{max} %	ΔV, %
	I_{d1}, MPa·ms	ν_{s1}	B_{s1}, sm/ms/ (0.1·MPa)$^{0.8}$	I_{d2}, MPa·ms	ν_{s2}	B_{s2}, sm/ms/ (0.1·MPa)$^{0.8}$	ψ_0	Particle burning surface	ν_c	B_c, sm/ms/ (0.1·MPa)$^{0.5}$			
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*
1	120	0.8	0.0101934	190	0.8	0.02099355	1.0	–	–	–	+50	5.9	3.2
			0.0086562			0.01782765					+20	0.1	0.1
			0.0060942			0.01255115					-30	14.5	7.2
			0.0050694			0.01044055					-50	21.4	7.5
2	120	0.8	0.028	–	–	–	0.2	constant	0.5	$3.19 \cdot 10^{-04}$	+50	9.2	1.4
										$2.70 \cdot 10^{-04}$	+20	0.1	0.1
										$1.88 \cdot 10^{-04}$	-30	19.3	2.2
										$1.55 \cdot 10^{-04}$	-50	20.0	20.6
3	120	0.8	0.028	–	–	–	0.2	constant	0.5	$2.13 \cdot 10^{-05}$	+50	9.1	1.4
										$1.80 \cdot 10^{-05}$	+20	0.2	0.1
										$1.25 \cdot 10^{-05}$	-30	19.5	2.3
										$1.03 \cdot 10^{-05}$	-50	20.5	20.8
4	120	0.8	0.028	–	–	–	0.2	constant	0.5	$2.13 \cdot 10^{-07}$	+50	9.2	1.4
										$1.80 \cdot 10^{-07}$	+20	0.1	0.1
										$1.25 \cdot 10^{-07}$	-30	19.3	2.2
										$1.03 \cdot 10^{-07}$	-50	20.0	20.7
5	120	0.8	0.033978	–	–	–	0.2	constant	0.5	$3.19 \cdot 10^{-04}$	+50	4.5	2.8
			0.028854							$2.70 \cdot 10^{-04}$	+20	0.1	0.1
			0.020314							$1.88 \cdot 10^{-04}$	-30	12.7	2.3
			0.016898							$1.55 \cdot 10^{-04}$	-50	10.3	18.4
6	105	0.8	0.0101934	190	0.8	0.02099355	1.0	–	–	–	+50	0.5	3.2
	120		0.0086562			0.01782765					+20	0.1	0.1
	150		0.0060942			0.01255115					-30	1.2	8.3
	240		0.0050694			0.01044055					-50	1.0	0.1
7	115	0.8	0.033978	–	–	–	0.2	constant	0.5	$3.19 \cdot 10^{-04}$	+50	0.6	3.3
	120		0.028854							$2.70 \cdot 10^{-04}$	+20	0.1	0.1
	205		0.020314							$1.88 \cdot 10^{-04}$	-30	0.8	0.2
	275		0.016898							$1.55 \cdot 10^{-04}$	-50	1.3	0.2

In the table, the following notation is used for the columns: *1* – number of the set of parameters in the law (type of law) of combustion in formulas (1) – (4); *2* – impulse to change the combustion mode; *3* – the exponent in the dispersion law of the TC; *4* – coefficient in the rate law of slow layer-by-layer TC burning; *5* – impulse of the beginning of the accelerated TC burning stage; *6* – the exponent in the TC dispersion law; *7* – coefficient in the law of accelerated TC burning rate; *8* – the initial conversion degree of particles dispersed from the combustion front; *9* – type of particles dispersed from the combustion front; *10* – the exponent in the particles combustion law; *11* – coefficient in the law of the particle burning rate; *12* – initial charge temperature; *13* – the mismatch of the calculated and experimental data on the maximum pressure; *14* – the mismatch of the calculated and experimental data on the muzzle velocity of the projectile.

Figure 3 (b) – (d) presents the results are presented. In all the plots, there is a discrepancy in the barrel velocity curve shape, with ΔV < 7.5 % at T_0 = – 50°C. There is a significant deviation in the pressure curve shape, ΔP_{max} < 21.4 %.



(a) – T_0 = +20 °C (b) – T_0 = +50 °C

(c) – T_0 = -30 °C (d) – T_0 = -50 °C

FIGURE 3. Experimental and calculated (obtained according to law **1**) dependences of pressure in the installation chamber and projectile velocity on time at various initial charge temperatures

In studies conducted at the second stage, it was considered that the combustion of the TC occurred in one stage, and the variant of the TC combustion model with the particles formation was considered. The temperature coefficient β_t was used to change the burning rate of propellant particles dispersed from the TC burning front at ψ_0 = 0.2. In this case, the rate of charge dispersion did not depend on temperature. It also investigated the effect of particle size on the agreement of calculated and experimental results (laws **2 – 4** in table). Table shows the burning rate of particles at a temperature of + 20 °C. The coefficient of the layer-by-layer particles burning rate B_c, used in the particles burning law (formula (4)), for the initial temperature T_0 was determined by the formula:

$$B_c(T_0) = B_c(20\,°C)\cdot[1 + \beta_t\,(T_0 - 20)], \qquad (6)$$

here B_c (20 °C) is determined at a temperature (20 °C).

Laws **2** – **4** of table make it possible to estimate the effect of the size of particles dispersing from the front of the TC on the ballistic shot parameters. Despite the discrepancy between the calculated and experimental data on the level of maximum pressure and the muzzle velocity of the projectile reached 21 %. For the studied particle sizes, the value of the maximum pressure and the muzzle velocity of the projectile, at the corresponding charge temperature, differ slightly. There is a weak effect of these TC combustion laws on the level of maximum pressure, which essentially depends on TC dispersion, which is most clearly shown in the combustion law **1**.

Therefore, at the third stage of research, the effect of the temperature coefficient β_t on the dispersion rate of the TC at ψ_0 = 0.2 and the layer-by-layer burning rate of the propellant particles was considered (law **5**, table). In this case, in the range of initial charge temperatures from -30 to +50 °C, the mismatch between the calculated and experimental data is: ΔP_{max} < 12.7 %, ΔV < 2.8 %. In the calculations carried out according to law **5**, it was found that at T_0 = –50 °C a decrease in the ballistic characteristics of the shot is observed. In the calculation, incomplete combustion of the monoblock part of the TC was obtained; the residue was 3.4 g, and the mass of unburned particles was 17.8 g; In this case, the mismatch ΔP_{max} =10.3 %.

Summarizing the results of the three stages of the study, it can be concluded that the change in the maximum pressure level in the range from -50 to +50 °C is associated with a change in the pulse of change in the TC burning mode, depending on the initial charge temperature. This is consistent with the results of the PP-1 paste propellant gauge tests in the temperature range from -50 to +50 °C, conducted by the propellant developer. It was noted that with a decrease in the initial temperature from high positive values (T_0 = +50 °C) to low negative (T_0 = –50 °C), the burning rate decreases, and the ignition delay increases. The propellant developer characterizes this phenomenon by means of the temperature coefficient of ignition delay ε_t of propellant, defined by the formula:

$$\varepsilon_t = \frac{\Delta t_{\text{ignition}}(T_2) - \Delta t_{\text{ignition}}(T_1)}{(T_2 - T_1)\cdot \Delta t_{\text{ignition}}(T_{20})}, \qquad (7)$$

here T_1 and T_2 are the temperature at the borders of the studied range.

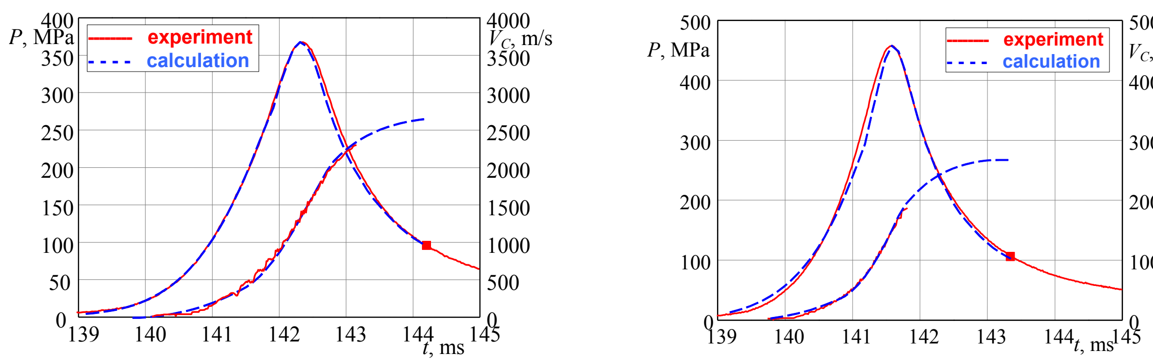
$\Delta t_{\text{ignition}}(T)$ is propellant ignition delay, determined according to manometric tests.

The value of the temperature coefficient of ignition delay ε_t for the studied propellant is ε_t = 0.0097 °C^{-1}. In the mathematical model used, accounting for this ignition delay is implemented by changing the magnitude of the impulse of switching to accelerated combustion mode TC I_d, depending on the initial temperature. The corresponding study was carried out at the fourth stage of calculations.

The burning law **6** is based on the burning end model, as is law **1**, but taking into account the dependence of I_{d1} impulse on the initial charge temperature. It allows to get a good agreement of the pressure curves forms, however, in the shape of the barrel projectile velocity curve, there are discrepancies in the graphs TC burning section. The mismatch of calculated and experimental data in the range of initial charge temperatures from -50 and -50 °C at the level of maximum pressure reaches 1.2 %, along the muzzle velocity of the projectile to 8.3 %.

In the law of combustion **7**, the coefficients of law **5** are taken as a basis with the addition of the dependence of I_{d1} on the initial charge temperature. There is a non-linear nature of the dependence change.

Figure 4 shows the calculated and experimental dependences of the pressure in the installation chamber and the projectile velocity on time, obtained by law **7** at the initial charge temperature from -50 to +50 °C.



(a) – T_0 = +20 °C (b) – T_0 = +50 °C

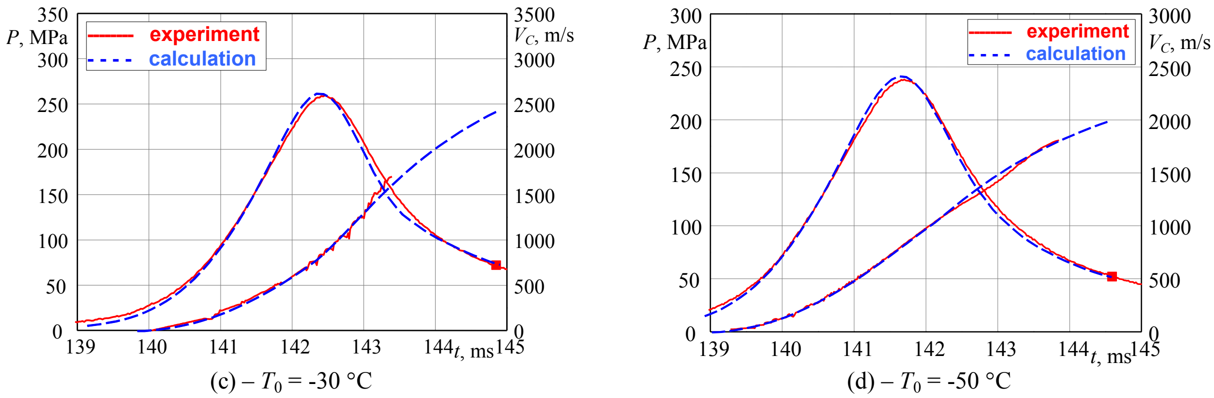


FIGURE 4. Experimental and calculated (obtained according to law **7**) dependences of pressure in the installation chamber and projectile velocity on time at various initial charge temperatures

In the calculations at $T_0 = -30$ and $T_0 = -50$ °C, incomplete combustion of the monoblock part of the TC is observed, the residue was 3.0 and 43.4 g, respectively, and unburned particles - 19.5 and 18.5 g, respectively. At the same time, there is a good agreement between the forms of pressure curves and the projectile velocity in the barrel, the mismatch between the calculated and experimental data in the range of initial charge temperatures from -50 to +50 °C in terms of maximum pressure reaches 1.3%, in terms of the muzzle velocity is up to 3.3 %.

Figure 5 presents the dependences of the change in the transition impulses to the accelerated TC combustion mode I_d on the initial charge temperature obtained in laws **6** and **7**. It can be seen that for the studied propellant in the composition of the TC, the obtained dependences are non-linear in nature and therefore cannot be matched with the temperature coefficient of ignition delay ε_t having a linear character. The result obtained seems to be related to differences in propellant combustion under the conditions of the shot with the TC and the manometric unit. In particular, under the conditions of the manometric unit, experiments are carried out at a lower level of maximum pressure, and a change in the mode of TC propellant combustion is not recorded. In this regard, when conducting parametric studies with the given type of charge, the value of the ignition delay is more correctly determined by the value of the coefficient I_{d1} formula (1).

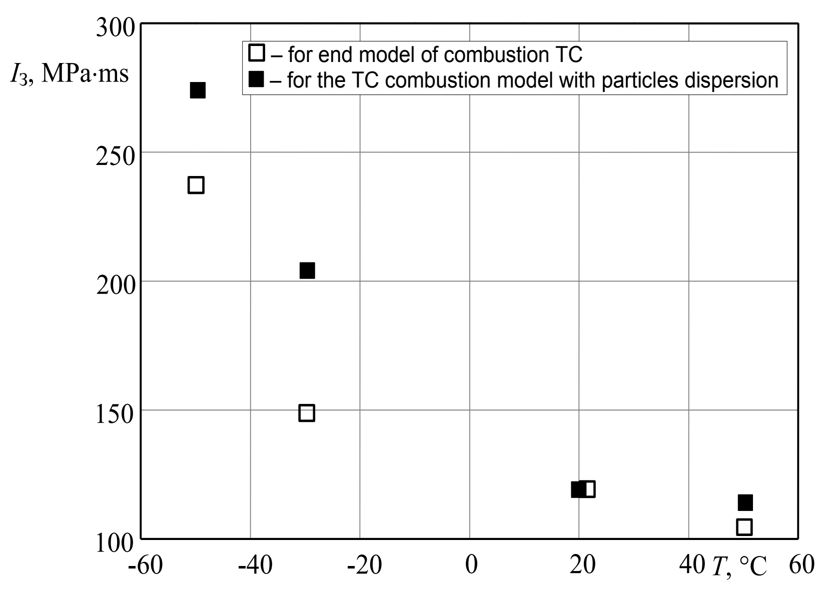


FIGURE 5. The dependence of the change of the impulse of transition to the accelerated combustion mode of the I_d propellant on the initial charge temperature

CONCLUSION

When using the temperature coefficient of the layer-by-layer burning rate β_t defined in the manometric tests, the burning rate for the butt model of the TC combustion (ψ_0 = 1) shows a discrepancy in the shape of the pressure and velocity curves in the barrel. In this case, the mismatch between the calculated and experimental data reaches the following values: by the magnitude of the muzzle velocity of the projectile is 7.5 %, by the maximum pressure is 21.4 %. Taking into account the dependence of I_{d1} on the initial charge temperature, the discrepancy in terms of the maximum pressure reaches 1.2 %, in terms of the muzzle velocity of the projectile is up to 8.3 %.

To calculate the ballistic characteristics of the shot with the TC, it is necessary to take into account the temperature coefficient β_t in the TC dispersion velocity, the layer-by-layer burning rate of dispersed propellant particles, as well as the dependence of the TC I_d accelerated burn impulse on the initial charge temperature, this allows the good agreement on the shape of the change chamber pressure and the barrel projectile velocity curves. The mismatch between the calculated and experimental data in the range of initial charge temperatures from -50 to +50 °C at the maximum pressure does not exceed 1.3 %, and the muzzle velocity of the projectile is 3.3 %.

NOMENCLATURE

β,θ tabular coefficients influence of the initial temperature
Ii ignition delay impulse (MPa·ms)
u_i burning rate (sm/ms)
B_i rate factor (sm/ms/(0.1·MPa)$^{\nu}$)
U_c burning rate of particles
P pressure (MPa)
ν_i exponential coefficient
Ψ_0 initial degree of particle conversion
V_C velocity in the barrel (m/s)
T_0 initial temperature of charge (°C)
β_t temperature coefficient of burning rate
ε_t temperature coefficient of ignition delay
$\Delta t_{\text{ignition}}$ propellant ignition delay

Abbreviation

TC travelling charges
PP pasty propellants

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