Investigation of influence of propellant charge temperature on gun firing phenomenon

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Abstract: *The temperature of propellant charge, like the level of operating wear of barrel inner surface, influences on pressure impulse of propellant gases inside the barrel during firing process. Value of pressure impulse decides on muzzle velocity of projectile and creates input data to determine projectile trajectory and its terminal ballistics parameters. Existing shooting tables of different weapon systems, enabling precise firing, are based on experimental (very expensive and time-consuming) investigations leading in different ambient temperatures (conditions of operating). Contemporary computer technology makes possible automatic fire control system creation based on solution of closed equation system describing the motion of projectile inside and out of the barrel, taking into consideration influence of different disturbances (including propellant charge temperature deviation). The results of a single-base propellant research with different initial temperature of charges are presented in this paper. Basic ballistic properties, such as the force, covolume and burning rate factor were calculated on the basis of measurements of pressure of propellant gases versus time in the closed vessel. Results of experimental investigations and calculations show influence of initial temperature of charges especially on burning rate.*

1. Introduction

Engineering design process of gun is realised on the basis of input data partly providing by mathematical solution of the thermodynamic interior ballistic model with global parameters [5] created for interior ballistic trajectory simulation of projectiles. To obtain a complete picture of the internal ballistic cycle we need some experimental data: the force f and the covolume α of propellant gases - to calculate the velocity V and the travel l of projectile and the pressure p of powder gases (pressure acting on the base of the projectile with mass m)

$$p(t) = \frac{f \cdot \omega \cdot \psi(t) - \theta \cdot \varphi \cdot \dfrac{m \cdot V(t)^2}{2}}{W_0 + s \cdot l(t) - \dfrac{\omega}{\delta}\left(1 - \psi(t)\right) - \alpha \cdot \omega \cdot \psi(t)}, \tag{1}$$

and linear burning rate law

$$u = u_1 \cdot p, \tag{2}$$

to calculate - in the case of geometric, regular shape of powder grains with smooth surface S_1 and volume Λ_1 - the mass rate of propellant burning which may be expressed as

$$\frac{d\psi}{dt} = \frac{S_1}{\Lambda_1} \cdot \sigma \cdot u = \frac{S_1}{\Lambda_1} \cdot \sigma \cdot u_1 \cdot p, \tag{3}$$

Results of experimental and theoretical ballistic investigations of propellants with their different initial temperature t_0 have not been published widely. During interior ballistic analysis the force and covolume - the coefficients of the Noble-Abel equation of state - are usually treated as constant and temperature invariant in wide temperature range of operating of weapon. Only burning rate of propellant is treated as temperature-dependent by variation of burning rate coefficient u_1.

On the other hand contemporary ammunition must fulfil higher requirements than in the past and has to be safe in each climate zone, should have a high cook off stability in order not to undergo a self ignition reaction of the gun propellant while lying in the hot gun barrel. Therefore a new type of propellant is worked out – Low Temperature Coefficient (LTC) propellant [8]. The LTC gun propellants consist of a cristalline explosive, a nitrocellulose binder and a special plasticizer. The burning rate of LTC propellant hardly depends on the propellant initial temperature and therefore the maximum gas pressure in the gun does not as well. From internal ballistic point of view LTC propellants are very attractive in computer simulations of different gun systems operating.

2. Closed vessel firing tests

The results of experimental pirostatic research of a single-base propellant (table 1) at different initial temperatures of charges and varying loading densities are presented in this paper.

Table 1. Chemical composition of analysed single-base propellant

Ingredient	[%]
Nitrocellulose N = (13.17÷13.21)%	93
Volatile substances	max 3.3
Diphenylamine	1.0 ÷ 2.0
Camphor	max 1.8
Graphite	max 0.28

Experimental pirostatic investigations were carried out in 200 cm^3 volume closed vessel set for limited (experimental) range of loading densities and for three values of initial temperature of propellant: -50 °C, 20 °C (as normal temperature) and +50 °C, significant for military weapon (small arms) system. Technical parameters of used closed vessel, pressure measurement system and methodology of investigation were the same as described in STANAG 4115 (Edition 2). Propellant charges were kept for 24 hours at normal temperature or at extreme environmental temperature of use (-50 or +50) °C.

2.1. Force and covolume

The force constant f of the propellant composition and the covolume α of propellant gases are calculated on the basis of the results of the closed chamber firings and the experimental Noble-Abel equation of state

$$p_m (W_0 - \alpha \cdot \omega) = f \cdot \omega \,, \tag{4}$$

where: p_m - maximum pressure of powder gases; W_0 – volume of combustion chamber; ω - mass of propellant. Average values of maximum pressure of propellant gases for different loading densities Δ and different initial temperatures of propellant are presented in table 2.

Table 2. Results of closed vessel experiments

$\Delta = \omega/W_0$ [kg m^{-3}]	t_0 = -50 °C		t_0 = 20 °C		t_0 = 50 °C	
	p_m [MPa]	$\frac{p_m}{\Delta}$ [MJ kg^{-1}]	p_m [MPa]	$\frac{p_m}{\Delta}$ [MJ kg^{-1}]	p_m [MPa]	$\frac{p_m}{\Delta}$ [MJ kg^{-1}]
50	52.95	1.0590	54.15	1.0830	54.3	1.0860
100	114.0	1.1400	115.6	1.1560	117.4	1.1740
150	183.0	1.2200	186.85	1.2457	189.0	1.2600
200	260.7	1.3035	264.8	1.3240	268.0	1.3400

Measured maximum pressure of propellant gases and known conditions of experiments are basis of determination of Noble-Able equation parameters. According to procedure described in STANAG 4115, the force and covolume may be obtained in result of approximation of linear (presented below) form of Noble-Able equation

$$\frac{p_m}{\Delta} = f + \alpha \cdot p_m \,, \tag{5}$$

Results of force and covolume at different initial temperature of propellant are presented below.
a) at $t_0 = -50$ °C: $f = 1.0016$ MJ kg^{-1}, $\alpha = 1.172$ dm^3 kg^{-1},
b) at $t_0 = +20$ °C: $f = 1.0230$ MJ kg^{-1}, $\alpha = 1.154$ dm^3 kg^{-1},
c) at $t_0 = +50$ °C: $f = 1.0286$ MJ kg^{-1}, $\alpha = 1.186$ dm^3 kg^{-1}.

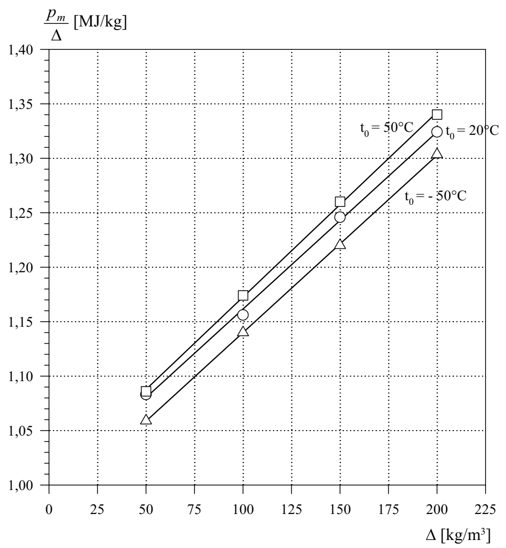

Fig. 1. Dependence $\frac{p_m}{\Delta}$ on loading density Δ and initial temperature t_0

2.2. Burning rate coefficient

In the case of geometric, regular shape of powder grains with smooth surface, the burning rate coefficient u_1 of the propellant is calculated on the basis of the results of the closed chamber firings too and the equation

$$u_1 = \frac{e_1}{I_k} = \frac{e_1}{\int_0^{t_k} p\,dt} \,, \tag{6}$$

where: e_1 – web thickness; I_k – impulse of pressure of propellant gases calculated from the start (0) to the end (t_k) of propellant combustion (process of gas creation).
Average results (for three different initial temperatures) of burning rate coefficient are presented below:
a) at $t_0 = -50$ °C: $u_1 = 0.43 \cdot 10^{-9}$ [m (sPa)$^{-1}$],
b) at $t_0 = +20$ °C: $u_1 = 0.50 \cdot 10^{-9}$ [m (sPa)$^{-1}$],
c) at $t_0 = +50$ °C: $u_1 = 0.63 \cdot 10^{-9}$ [m (sPa)$^{-1}$].
Presented above results show that the force constant and the burning rate coefficient are expressive dependent on initial temperature of propellant. Expressive increase or decrease of force constant and burning rate coefficient is the reason of changes in pressure impulse and muzzle velocity of projectile, and finally is the reason of changes in projectile range. Therefore force constant f and the linear burning rate coefficient u_1 should be modified by temperature functions. Temperature functions usually are defined as:

$$F_1(t_0)=\frac{f(t_0)}{f(t_n)}=1+a\cdot(t_0-t_n)\ , \tag{7}$$

$$F_2(t_0)=\frac{u_1(t_0)}{u_1(t_n)}=[1-b(t_0-t_n)]^{-1}\ , \tag{8}$$

where: t_n - normal temperature; a, b – propellant constants.

Figures 2 and 3 present diagrams of force constant and burning rate temperature functions (F_1 and F_2) for analysed propellant.

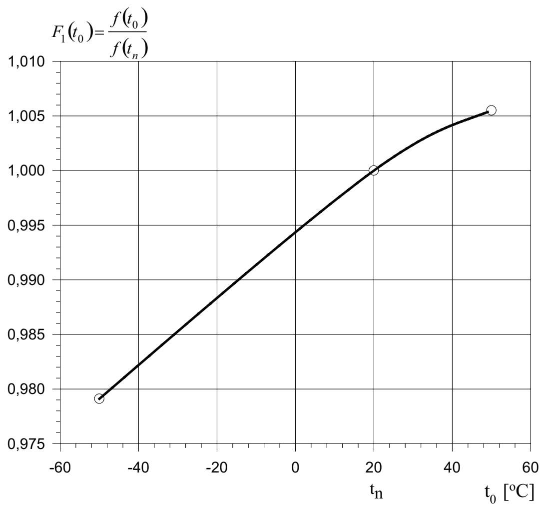

Fig. 2. Force constant temperature function vs. temperature t_0

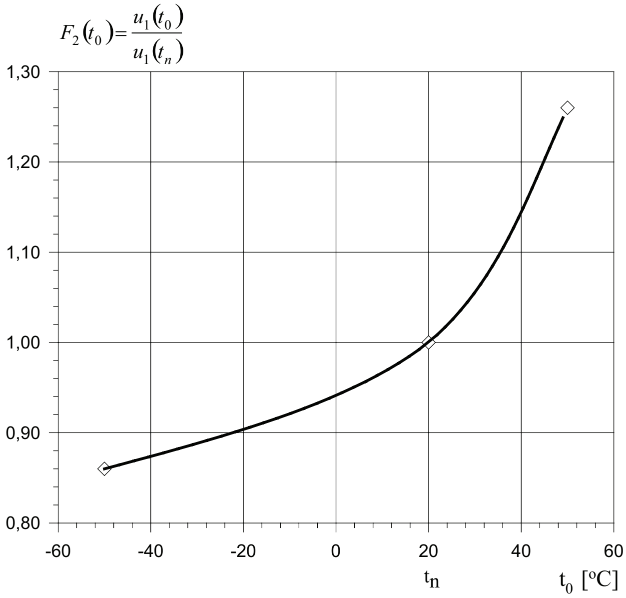

Fig. 3. Burning rate temperature function vs. temperature t_0

According to above diagrams, final forms of temperature functions (7) and (8) are presented below:
- force constant temperature function, for all temperature range $t_0 = (-50 \div +50)$ °C:

$$F_1(t_0) = \frac{f(t_0)}{f(t_n)} = 1 + 0.281 \cdot 10^{-3} \cdot (t_0 - t_n)\ , \qquad (7a);$$

- burning rate temperature function:
- for temperature range $t_0 = (-50 \div +20)$ °C:

$$F_2(t_0) = \frac{u_1(t_0)}{u_1(t_n)} = \left[1 - 2.326 \cdot 10^{-3}(t_0 - t_n)\right]^{-1}, \qquad (8a)$$

- for temperature range $t_0 = (+20 \div +50)$ °C:

$$F_2(t_0) = \frac{u_1(t_0)}{u_1(t_n)} = \left[1 - 6.878 \cdot 10^{-3}(t_0 - t_n)\right]^{-1}, \qquad (8b)$$

3. Conclusion

Results of experimental investigations of analysed single-base propellant and calculations show influence of initial temperature of charges especially on burning rate. Together with increase (or decrease) of initial temperature of propellant, the burning rate of propellant increases (or decrease) too and therefore total combustion time is shorter (or longer). Expressive increase or decrease of burning rate coefficient is the reason of changes in pressure impulse (maximum pressure) and muzzle velocity, and finally is the reason of changes in projectile range. For example Fig. 4 presents theoretical diagrams of pressure changes (with initial temperature of propellant) in hypothetical weapon system for analysed single-base propellant.

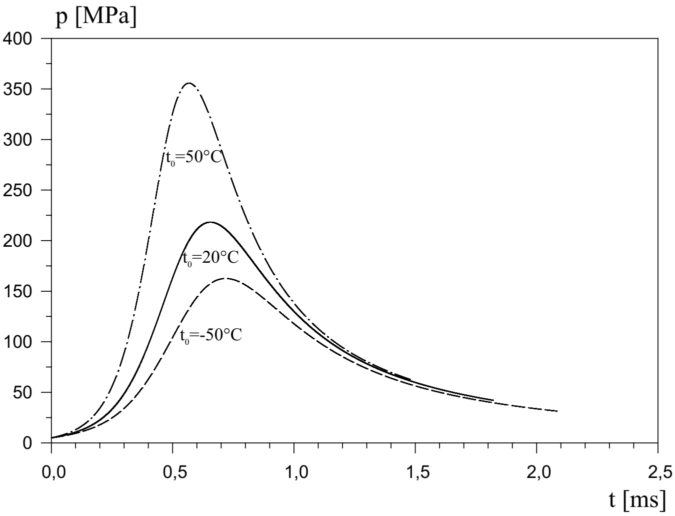

Fig. 4. Pressure p of propellant gases inside the barrel vs. time t

It means that fired projectile will fly with other trajectory in summer and with other trajectory in winter. Therefore it should be modified – separately for every kind and type of propellant - the mathematical model of shooting by taking into consideration individual temperature factor.

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