ISSN: 2414-1895 DOI: 10.6919/ICJE.201910_5(11).0025

Detonation Impact Characteristics of Nitrocellulose in Nail Gun

Cong Deng [a], Guangzhong Hu [b], Yue Lan [c], Liu Yuan [d], Duqing Qu [e]

School of Mechanical Engineering, Sichuan University of Science & Engineering, Zigong 643000, China

[a]susedengcong@163.com, [b]hgzdhx@163.com, [c]lanyue@inm.imech.ac.cn, [d]814252685@qq.com, [e]1432255348@qq.com

Abstract

Based on the basic theory of internal ballistics and detonation physics, this paper studies the detonation characteristics when nitrocellulose is exploded in nail guns. The energy source and energy conversion form of the impact force produced by explosion are determined in theory, and an example is provided for calculating the parameters of gunpowder of unusual types. Through the establishment of an impact test platform, the muzzle velocity of the piston rod under the impact of different mass explosives is determined by a high-speed camera. The explosive force of gunpowder is then calculated by theory. Finally, the ballistic efficiency is obtained in the 100-mm acceleration segment. As demonstrated by the results, the ballistic efficiency of gunpowder with different masses in the same acceleration segment is 25.9%, and the kinetic energy transformed by nitrocellulose of any mass can be calculated by this value.

Keywords

Internal ballistics, detonation physics, nitrocellulose, nail gun, explosion, ballistic efficiency, kinetic energy.

1. Introduction

Gunpowder is a kind of anakinetomere and can release a significant amount of gas product and heat energy after combustion. Nitrocellulose is a common gunpowder, and its explosion can produce a huge impact force; thus, nitrocellulose has been increasingly more widely applied in the civil field. The nail gun achieves its purpose of tightening via the huge impact force produced by the explosion of nitrocellulose. However, due to the large amount of energy of gunpowder, there are still many difficulties in adjusting the relationship between the quality and power of gunpowder. In interior ballistics, there are two processes of gunpowder explosion: detonation and the impact of the propellant. At present, most of the research on interior ballistics is developed from classical interior ballistics and detonation physics. Many researchers have found that mathematical and physical models of interior trajectory based on classical interior ballistics cannot describe the complex phenomena in the explosion process. Therefore, scholars have researched the combustion characteristics of gunpowder [1, 2], the spread of detonation waves [3, 4], the influence of the particle state on the explosion [5, 6], and other aspects based on classical internal ballistics. The studies have utilized many research methods; for example, Matúš [7] studied the spreading of a variety of types of simulation explosive waves via methods such as a pressure-time function, compression balloon, mapping algorithm, and solid TNT by LS-dyna simulation. Ma [8] modified the classical internal ballistics equation and put forward a modified equation of breech pressure that considered the influence of changes in the specific heat ratio and constant-volume specific heat of the air resistance, combustion velocity, and gunpowder gas. Andreevskikh [9] studied the combustion evolution and mode conversion of these kinds of gunpowder in slits, and obtained the rates and critical conversion

ISSN: 2414-1895 DOI: 10.6919/ICJE.201910_5(11).0025

pressures of several common explosives under two combustion modes via analysis. Although many scholars have studied interior ballistic problems from various aspects, little research has been conducted in the civil field. Combined with the engineering application of the nail gun, this paper explores the relationship between the mass of nitrocellulose and the kinetic energy transformation of gunpowder to provide a basis for the kinetic energy control of nail guns.

2. Theoretical Models

To improve research efficiency, many scholars have simplified the research process by simulation [10-12], but as is evident from these studies, the current simulation technology is not sufficiently mature. Because of the complexity of the explosion process, it is necessary to establish theoretical models for different situations.

In the present research, the nail gun is transformed into a civil fastening device based on the gun. Its working principle is illustrated in Fig. 1. All of its work is carried out in ballistics. To study the relationship between gunpowder mass and piston rod kinetic energy, the establishment of a relatively systematic theoretical calculation model is required.

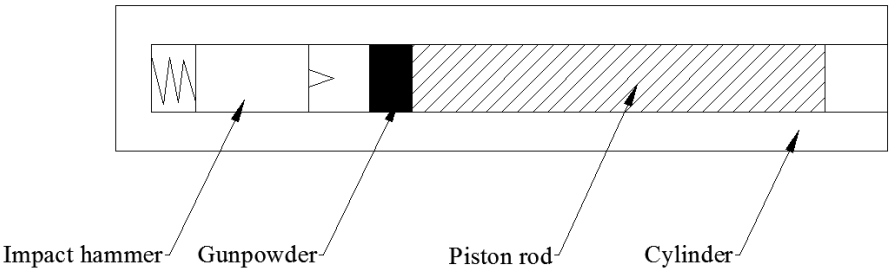


Fig.1.Working principle diagram of the nail gun.

In the field of interior ballistics research, researchers believe that the process of gas driving an object to move is actually a process of the energy released by gunpowder transforming to other forms of energy after combustion. Based on the law of conservation of energy, scholars propose the basic equation of interior ballistics as follows [14]:

$$sp\left(l_{\psi}+l_{a}\right)=f\omega\psi-\frac{\theta}{2}\varphi mv^{2} \tag{1}$$

where

$$l_{\psi}=l_{0}\left(1-\frac{\Delta}{\rho_{p}}\left(1-\psi\right)-\alpha\bullet\Delta\bullet\psi\right) \tag{2}$$

$$\theta=\frac{f}{Q_{v}} \tag{3}$$

$$\varphi=1+\xi \tag{4}$$

As shown in the research by Cook [13], the covolume α is a function of density. For most percussion powder and high explosives with a density greater than 1 g/cm^3,

$$\alpha=exp\left(-0.4\rho\right). \tag{5}$$

In gunpowder science, $f=RT_b$ is the gunpowder impetus [15] in units of J/g, and is the power capability of gunpowder per unit mass. Therefore, the power capability of gunpowder with a certain quality can be expressed as:

$$f_0=\omega f=\omega RT_b, \tag{6}$$

ISSN: 2414-1895 DOI: 10.6919/ICJE.201910_5(11).0025

where $\frac{f\omega\varphi}{\theta}$ is the total energy released by gunpowder combustion, $\frac{\varphi}{2}mv^2$ is the various work by gunpowder gas expansion, and $\frac{Sp\left(l_\psi + l\right)}{\theta}$ is the state potential energy of gunpowder gas, i.e., the heat energy stored in the gas. In $\frac{\varphi}{2}mv^2$, 90% of the energy is converted into the kinetic energy of the accelerated object as the main work, while the other 10% is the second work. If the second work is ignored, and if only the main work $\frac{1}{2}mv^2$ is considered, its conversion efficiency can be expressed as:

$$\gamma = \frac{\frac{1}{2}mv^2}{\frac{f\omega}{\theta}}. \tag{7}$$

In interior ballistics, γ is called the ballistic efficiency [14]. Combined with the above research findings, it can be determined that the process of gas work is actually the process of heat energy conversion. Therefore, γ can also be expressed as:

$$\gamma = \frac{T_b - T_g}{T_b\varphi}. \tag{8}$$

As can be discerned from the above equation, when the exact value of γ of a certain kind of gunpowder is known, the relationship between the mass and kinetic energy of the powder in a certain acceleration section can be obtained by calculation. In practical engineering applications, the acceleration ability of a certain mass of gunpowder can be directly obtained by this function.

If the gunpowder impetus of nitrocellulose is to be determined, the explosion temperature of the nitrocellulose must first be obtained. The explosion temperature can be calculated by the Custer method [13]:

$$Q_v = \sum n_i \overline{c_v} \bullet t \tag{9}$$

$$\overline{c_v} = \alpha + \beta t \tag{10}$$

The detonation temperature can be calculated by the following equation:

$$T_b = 298 + \frac{-\sum n_i\alpha + \sqrt{\left(\sum n_i\alpha\right)^2 + 4\sum n_i bQ_v}}{2\sum n_i\beta} \tag{11}$$

where the values of α and β can be obtained from Custer's average molecular heat capacity formula as follows:

Diatomic gas: $\overline{c_v} = 20.08 + 1.883\times10^{-3}t$

Vapor: $\overline{c_v} = 16.74 + 8.996\times10^{-3}t$

Triatomic gas: $\overline{c_v} = 40 + 2.427\times10^{-3}t$

Tetratomic gas: $\overline{c_v} = 41.84 + 1.883\times10^{-3}t$

Pentatonic gas: $\overline{c_v} = 50.21 + 1.883\times10^{-3}t$

Carbon: $\overline{c_v} = 25.1$

ISSN: 2414-1895 DOI: 10.6919/ICJE.201910_5(11).0025

The maximum detonation heat can be calculated by the maximum exothermic principle [13], and it can then be used as the actual detonation heat via multiplication by the true coefficient. For the pure explosive $C_aH_bO_cN_d$, the detonation heat can be obtained by the following equation:

If A ≥ 100%,

$$Q_V = K\left(393.2a + 120.3b\right) \tag{12}$$

If A < 100%,

$$Q_V = K\left(196.6c + 21.9b\right) \tag{13}$$

$$K = 0.37\left(100A\right)^{0.24} \tag{14}$$

$$A = \frac{c}{2a + b/2} \tag{15}$$

3. Experiment and Calculation

3.1 Experimental Material

Nitrocellulose is a kind of gunpowder generated by the nitration of nitric acid. Due to the difference between their nitrogen contents, there is also a large difference in their power. At present, there are many methods for the measurement of the nitrogen content of nitrocellulose [15, 16]. This study carried out experiments on some kinds of civil nitrocellulose. The analysis was carried out by an elemental analyzer, and the contents of C, H, O, and N elements were determined and are presented in Table 1.

Tab.1.Elemental contents of certain types of nitrocellulose.

Element	C	H	O	N
Content(%)	26.5	5.3	56.6	11.6

The molecular formula of gunpowder can be expressed as $C_aH_bO_cN_d$. The oxygen balance of the gunpowder combustion reaction can be determined by the following formula: c - (2a + b/2). If c - (2a + b/2) > 0 or = 0, it reflects a positive oxygen balance and a zero oxygen balance, respectively, and it is not necessary for the oxygen to be obtained from the outside during combustion. If the value is less than 0, the oxygen element needs to be obtained from outside. When the value is less than 0, the oxygen balance is negative, and oxygen is required to be obtained from the outside if the gunpowder is to burn completely.

The chemical formula of nitrocellulose can be expressed as $C_6H_{14.4}O_{9.6}N_{2.3}$, and its relative molecular mass is M_H = 272.2. Therefore, the combustion of the gunpowder has a negative oxygen balance. For the gunpowder with a negative oxygen equilibrium, according to the maximum exothermic principle, i.e., all oxygen elements are prioritized for the generation of H_2O, the remaining oxygen elements generate CO_2, and the excess carbon is converted into solid carbon. The equilibrium equation of combustion can be expressed as:

$$C_6H_{14.4}O_{9.6}N_{2.3} \rightarrow 1.2CO_2\uparrow + 7.2H_2O\uparrow + 1.15N_2\uparrow + 4.8C\,. \tag{16}$$

From equations (9-15), it can be determined that the detonation heat of nitrocellulose Q_v = 2092.6 J/g, and the detonation temperature T_b = 3965.1 K. The gunpowder impetus of nitrocellulose can therefore be obtained: f = 1345.6 J/g.

The relative molecular mass of the gas is:

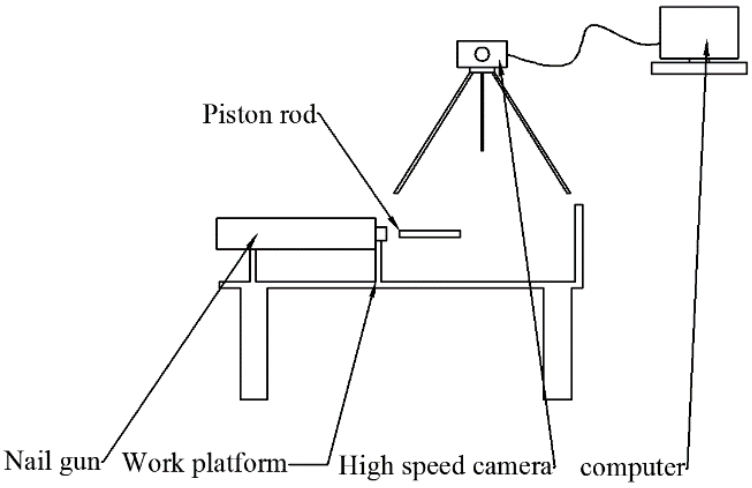
$$M_H = \frac{272.2 - 4.8\times 12}{9.55} = 24.5\,g/mol\,.$$

ISSN: 2414-1895 DOI: 10.6919/ICJE.201910_5(11).0025

For the experiment, 10 groups of nitrocellulose were selected. The initial charge density was 1.35 g/cm^3, the piston rod mass was 30.9 g, the material was 60Si_2Mn, the ballistic diameter was 6.5 mm, and the acceleration range was 100 mm.

3.2 Experimental Scheme

The experimental device is shown in Fig. 2. It includes a percussion device, a worktable, a high-speed camera, and a computer. The principle of the percussion device causes the gunpowder explosion via impact; it contains the percussion device and the chamber section for the work of the gunpowder explosion. The high-speed camera can catch the motion of the piston rod at 500 frames per second. After catching, the images are directly stored in the computer. Finally, the motion speed of the piston rod can be obtained by handling the captured pictures.



(a) Schematic diagram

(b) Photo of the real object

Fig.2.The experimental setup.

3.3 Result and Discussion

The impact work effect of nitrocellulose with different masses on the piston rod was obtained by the experiment, as shown in Figs. 3-5. Only 3 groups of mass experimental images are presented.

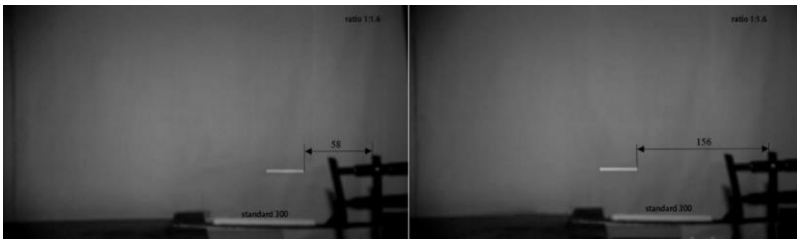


Fig.3.Experimental rendering of 0.1831 g gunpowder.

ISSN: 2414-1895 DOI: 10.6919/ICJE.201910_5(11).0025

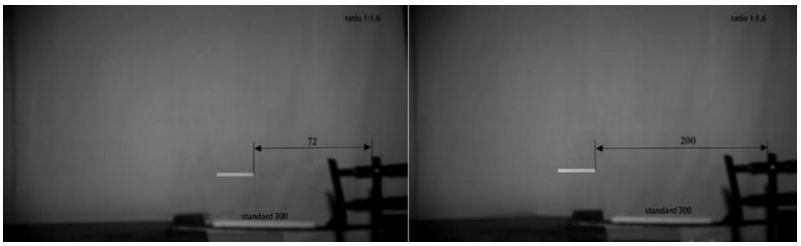


Fig.4.Experimental rendering of 0.2968 g gunpowder.

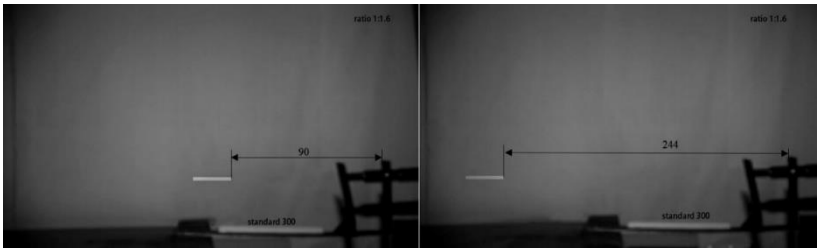


Fig.5.Experimental rendering of 0.4073 g gunpowder.

In the images, the standard is a preset standard part with a length of 300 mm. The scale of the image is determined to be 1:1.6 by image processing, which means that one pixel represents the actual distance of 1.6 mm. The numbers in the images represent the displacement distances of the piston rod in the images. For example, in Fig. 3, 58 pixels are displaced in the first frame, and 156 pixels are displaced in the second frame. Therefore, after calculation with its average speed of 78.4 m/s, the movement distance of the piston rod within the time interval of 0.002 s is determined to be 156.8 mm. Combined with Eq. (4), the kinetic energy of the piston rod and the total energy and ballistic efficiency γ of nitrocellulose can be determined, as presented in Table 2.

Tab.2.Experimental results.

$NO.$	1	2	3	4	5	6	7	8	9	10
Mass(g)	0.1831	0.2071	0.2356	0.2408	0.2968	0.31845	0.3434	0.3666	0.4073	0.43696
$\frac{1}{2}mv^2(J)$	94.66	100.17	128.37	130.35	161.48	176.97	186.34	207.22	233.74	252.31
$\frac{f\omega}{\theta}(J)$	384.97	435.43	495.35	506.29	624.03	669.55	722	770.78	856.36	918.72
$\gamma(\%)$	24.59	23	25.91	25.75	25.88	26.43	25.81	26.88	27.29	27.46

As can be seen from Fig. 6, within the same range, the ballistic efficiency always fluctuates up and down under a scope. After calculating its arithmetic average, the γ-value of the straight line shown in the figure is obtained as $\gamma_a = 25.9\%$.

Combined with Eq. (4), the relationship between the mass and energy of nitrocellulose can be obtained by the γ_a-value, as shown in Fig. 7. In engineering applications, if the power is expressed by the acceleration ability of an object, in this range, the kinetic energy or the power of nitrocellulose of a specific mass can be calculated by substituting γ_a into Eq. (4). This research can guide the design of different specifications of nail projectiles suitable for different occasions (different types of nail projectiles with different masses of gunpowder), and can provide assistance for the design and production of nail guns.

ISSN: 2414-1895 DOI: 10.6919/ICJE.201910_5(11).0025

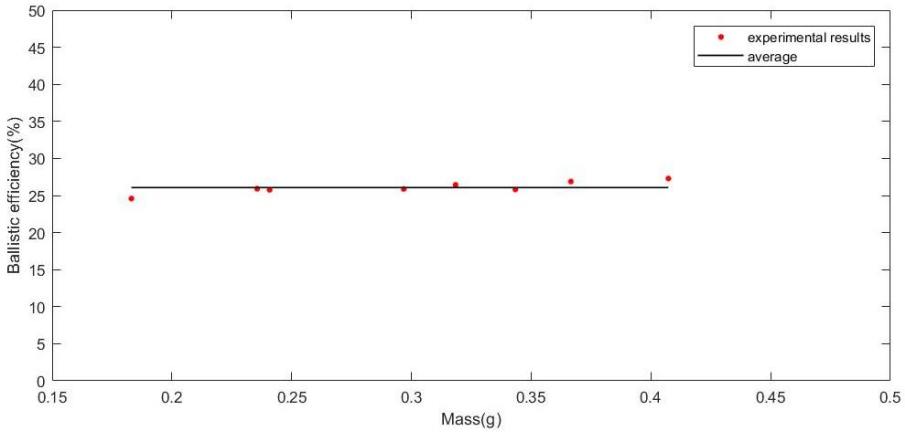


Fig.6.The relationship between different masses and ballistic efficiencies of nitrocellulose.

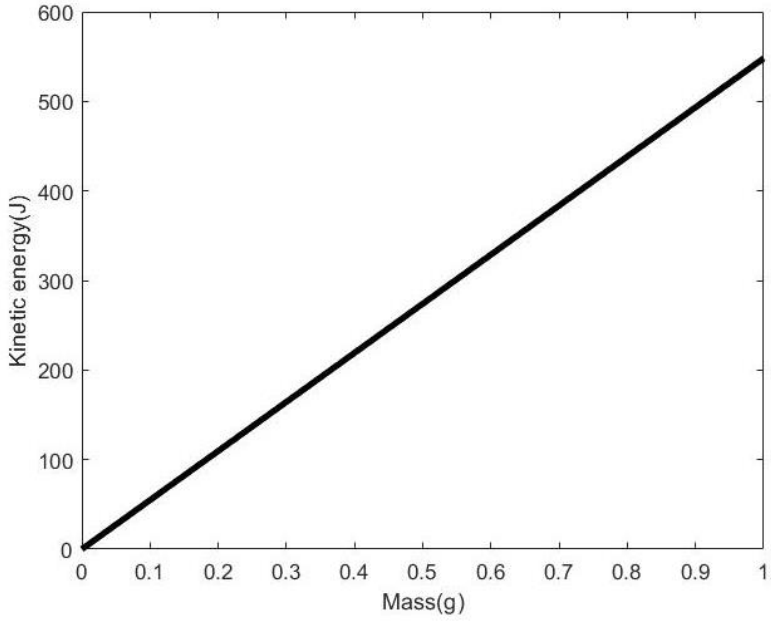


Fig.7.The relationship between different masses and kinetic energies of nitrocellulose.

4. Conclusion

In this paper, the chemical formula of nitrocellulose in this model was first determined by elemental analysis, and its performance parameters, including detonation heat, detonation temperature, and explosive force, were then determined by theoretical calculation. Finally, the ballistic efficiencies of nitrocellulose of different qualities were obtained via experimentation and calculation. The conclusions can be drawn as follows.

For the same type of gunpowder, there is little difference in the ballistic efficiency of gunpowder with different masses in the same acceleration segment. Additionally, the ballistic efficiency of nitrocellulose with different masses is approximately equal to 25.9% under the experimental conditions of a ballistic diameter of 6.5 mm and an acceleration range of 100 mm.

References

[1]Leciejewski Z.K., and Surma Z. Effect of application of various ignition conditions in closed-vessel tests on burning rate calculation of a fine-grained propellant // Combustion Explosion Shock Waves. 2011. Vol.47, No. 2. P. 209-216.

[2]Leonov, G. N. Some aspects of the effect of the porosity of the condensed phase on the combustion of nitrocellulose propellants // Combustion Explosion Shock Waves. 2008. Vol.44, No. 5. P. 547–551.

ISSN: 2414-1895 DOI: 10.6919/ICJE.201910_5(11).0025

[3]Mouritz, A. P. Advances in understanding the response of fibre-based polymer composites to shock waves and explosive blasts // Composites Part A: Applied Science and Manufacturing. 2019. Vol.125. P. 1-29.

[4]Artero-Guerrero, J., Pernas-Sánchez, J., and Teixeira-Dias, F. Blast wave dynamics: The influence of the shape of the explosive // Journal of Hazardous Materials. 2017. Vol.331. P. 189–199.

[5]E. Keller, G.,and W. Horst, A. The Effects of Propellant Grain Fracture on the Interior Ballistics of Guns[R]. 1989. Vol.53.

[6]A E Kiryushkin, and L L Minkov. Solution of internal ballistic problem for SRM with grain of complex shape during main firing phase. // Journal of Physics: Conference Series. 2017. Vol.894, No. 1. P.1-7.

[7]Matúš Ivančo, Romana Erdélyiová, and Lucia Figuli. Simulation of detonation and blast waves propagation. // Transportation Research Procedia. 2019. Vol.40. P.1356-1363.

[8]Yan Ma, Fengqiang Nan, and Weidong He. Corrected Internal Ballistic Simulation of High Chamber Pressure Gun. // IOP Conference Series: Materials Science and Engineering. 2018. Vol.439, No. 3. P. 1-6.

[9]Andreevskikh LA, Vakhmistrov SA, and Pronin DA. Convective combustion in the slot of an explosive charge. // Combustion Explosion Shock Waves. 2015. Vol.51, No. 6. P. 659-663.

[10]Diachkovskii, A. S., Zykova, A. I., Ishchenko, A. N., et al. Mathematical model and software for investigation of internal ballistic processes in high-speed projectile installations. // Journal of Physics: Conference Series. 2017. Vol.919, No.1. P. 1-11.

[11]Lu, X., Zhou, Y., and Yu, Y. Experimental Study and Numerical Simulation of Propellant Ignition and Combustion for Cased Telescoped Ammunition in Chamber. // Journal of Applied Mechanics. 2010. Vol.77, No. 5. P. 1-5.

[12]Chen, X., Lu, F., and Zhang, D. Penetration trajectory of concrete targets by ogived steel projectiles–Experiments and simulations. // International Journal of Impact Engineering. 2018. Vol.120. No. 202–213.

[13]Baopi Zhang, Qingming Zhang, and Fenglei Huang. Detonation physics. Ordnance industry press, B.J., China, 2001.

[14]Zhiming Jin. Interior ballistics of guns. Beijing institute of technology press, B.J., China, 2004.

[15]Alinat, E., Delaunay, N., and Costanza, C.et al. Determination of the nitrogen content of nitrocellulose by capillary electrophoresis after alkaline denitration. // Talanta. 2014. Vol.125. P. 174–180.

[16]López-López, M., Alegre, J. M. R., and García-Ruiz, C.,et al. Determination of the nitrogen content of nitrocellulose from smokeless gunpowders and collodions by alkaline hydrolysis and ion chromatography. // Analytica Chimica Acta. 2011. Vol.685, No. 2. P. 196–203.

Nomenclature	
S	the cross-section area of gunpowder
p	the gas intensity of pressure
l_0	the initial gunpowder length
l_a	the increment of the route
Δ	the loading density of gunpowder
ρ_p	the density of the solid phase
ψ	the burned percentage (the value of 1 is used under normal conditions)
ξ	the ratio of the second work to major work
α	the covolume

ISSN: 2414-1895 DOI: 10.6919/ICJE.201910_5(11).0025

ρ	the density of gas
f	the gunpowder impetus
T_b	the detonation temperature
γ_a	the average of ballistic efficiency
ω	the mass of gunpowder
R	the universal gas constant
R_0	the perfect gas constant (about8.31441±0.00026J/(mol·K))
M_H	the relative molecular mass of the detonation gas
γ	the ballistic efficiency
T_g	The real-time temperature
$\sum \overline{c_v}$	the sum of the average molecular thermal volumes of explosive products between 298 and T_b (K) (J/(mol·K))
t	the net increase temperature of explosive products from 298 K ~T_b
n_i	the amount of substance of detonation product (mol)
Q_v	the detonation heat
K	the coefficient of authenticity
A	the oxygen coefficient