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Research on the Parameters of Jet-Abrasive Devices for Battlefield Gun Barrel Restoration

V. Savchenko[1*], A. Derevjanchuk[2], V. Baha[2], I. Pavlenko[2], R. Vozniak[3], O. Sampir[3], Y. Horbachova[3], and I. Novikova[3]

[1] *State University of Information and Communication Technologies, Kyiv, Ukraine*
[2] *Sumy State University, Sumy, Ukraine*
[3] *The National Defence University of Ukraine, Kyiv, Ukraine*

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Abstract:

This article investigates a jet-abrasive installation with a device for cleaning gun barrels, developed for field conditions. The possibility of efficient cleaning of artillery barrel surfaces without the need for stationary conditions is evaluated, which is crucial for maintaining the combat readiness of equipment during intensive combat operations. A special guiding device holding multiple sandblasting nozzles is used, ensuring an optimal flow of the air-abrasive mixture and improving the processing efficiency. The conducted experiments show the significant impact of the nozzle geometry on surface treatment parameters, demonstrating that the use of a special device enhances both the economic efficiency and processing speed. The study emphasizes the importance of developing technologies that reduce the time spent on restoration work while ensuring the effectiveness of cleaning procedures in the field.

Keywords:

jet-abrasive cleaning, gun barrel maintenance, field restoration, sandblasting nozzles, air-abrasive mixture, surface treatment, nozzle geometry, artillery system maintenance, corrosion removal

1 Introduction

The Russian-Ukrainian war consistently highlights the crucial role of artillery in modern combat. The intensive use of artillery on the battlefield accelerates the wear of barrels, breechblocks, and other critical components, necessitating rapid restoration without reliance on costly repair facilities. The barrel is the core element of any gun,

* *Corresponding author: Cybersecurity Department, State University of Information and Communication Technologies, Solomianska 7, Kyiv, Ukraine. Phone: +380 675 04 60 12, E-mail: savitan@ukr.net. ORCID 0000-0002-3014-131X.*

and its durability is primarily affected by rifling wear due to combat use and corrosion caused by environmental factors such as rain, snow, fog, and sharp temperature fluctuations. Restoring artillery in the field is a complex challenge that requires specialized equipment and trained personnel. Consequently, current research efforts are focused on developing restoration technologies that minimize dependence on stationary facilities and reduce the time required for repairs.

2 Statement of Research Problem

Fig. 1 presents individual barrel fragments that have undergone wear due to both combat use (battle damage) and environmental exposure. The most critical factor affecting the timeliness and quality of barrel restoration is corrosion. Rust poses a significant threat not only to the internal bore of the barrel but also to other weapon components. Even when using metals resistant to high temperatures and pressure, as well as barrels with chrome-plated internal coatings, their operational and combat characteristics do not always remain intact. This degradation compromises structural integrity to the extent that barrels often require replacement.

Fig. 1 General view of the surface of the borehole

Various methods for cleaning barrel bores, including rust removal, are well-documented. A traditional approach involves manual cleaning with a bore brush, a labor-intensive and time-consuming procedure. Its efficiency can be slightly improved by using special chemical agents and cleaning devices. However, for barrels exposed to open-air conditions for prolonged periods before maintenance, the effectiveness of this method remains critically low. Additionally, the process of bore cleaning and carbon residue removal (including washing) typically requires an average of 4 to 7 hours. Essentially, restoring a single barrel demands an entire workday [1]. Under conditions of intense combat operations, such lengthy restoration times are unacceptable.

3 Overview of Related Works

Various aspects of maintaining the technical condition of artillery systems have been previously discussed in publications [2-3] which identify the main problems faced by repair units during the restoration of artillery systems. The main causes of failures that occurred during the combat use of artillery systems and that affected the level of readiness of units were investigated. However, the issue of artillery barrel restoration has received insufficient attention in the academic literature.

Several methods have recently been proposed to strengthen the bore of a barrel. For instance, in [4-5], the authors propose a new surface hardening technology for strengthening the barrels of large-caliber artillery and tank guns based on surface plastic deformation of the inner surface of the bore. This type of strengthening is based on cold processing of the barrel bore with spherical deforming balls, which are installed on a massive cylindrical amplifier. As a result of such processing, residual compressive stresses are formed in the barrel bore material, which improves its surface microhardness. However, the authors' conclusions are based on previous studies of steel sleeves used in slurry pump systems for drilling wells. Therefore, future research should include laboratory testing of reinforced gun barrel models, exposing them to high-temperature heating and flame treatment to obtain practical results. Also, it is necessary to investigate how effective such strengthening can be and whether it will not lead to a change in the geometric dimensions of the barrel bore. Also, it seems that such technology can only be implemented in stationary conditions of a repair enterprise and is extremely difficult to use in field conditions.

In [6], research was conducted to develop technologies for extending the operational lifespan of gun barrels using the magnetron sputtering method. This approach enables the application of high-quality coatings with superior physical and technical characteristics. The developed metal sputtering system allows for refining the technological process of cleaning the inner surface of gun barrels with a diameter of at least 120 mm, followed by the deposition of both single-layer and multilayer protective coatings. Additionally, the cylindrical magnetron used in the process can operate in direct current, high-frequency, or pulsed modes, offering advantages in the technological efficiency of the coating process.

In [7], the author proposes a method for restoring internal surfaces based on vacuum arc deposition with cathodes made of nichrome alloy and steel. This method can also be applied to restore protective coatings on other key components of artillery systems, such as recoil cylinders and counterweight mechanisms.

In [8], a method for cleaning the internal and external surfaces of tubes is presented. This approach involves processing the cylindrical surface of tubes to remove contaminants and modify their surface using a high-concentration energy source in a vacuum environment with an inert working gas. The study employs an electron gas-discharge gun with a surface-specific power of up to 105 W/cm^2, capable of injecting conical and annular solid or multi-beam electron streams.

The author of [9] explores ways to enhance the efficiency of the micro-abrasive jet treatment process for cylindrical surfaces of dispersion-hardened alloys containing magnesium and silicon as primary alloying elements. To examine the maximum achievable depth, diameter, and width of the treated surface, a micro-abrasive jet device with a dual-chamber reservoir and dust absorber was used. Scanning electron microscope analysis revealed a correlation between surface roughness and the increase in applied pressure and nozzle diameter.

In [10], research on the efficiency of an improved ejector with an optimized flow profile based on the Vitozinsky curve is presented. The study results confirm the potential application of the Vitozinsky curve for ejector enhancement and provide theoretical guidelines for designing a new flow profile configuration.

In [11], the author investigated the impact of the high-pressure Common Rail nozzle design on hydrodynamic characteristics using a three-dimensional phase Doppler particle analyzer. As a result, trends in particle size distribution within the jets were identified. Numerical modeling of the phase diagram of water in pulsed water jets with nozzles of different designs was conducted, providing insights into the variation of jet distance and width.

The analysis of these and other publications suggests that ongoing research continues to focus on developing simple and cost-effective technologies for restoring artillery barrels directly on the battlefield, without the need to transport guns to repair facilities or involve highly skilled personnel. One of the promising methods is jet-abrasive treatment of barrel bores.

This study examines a jet-abrasive system with a custom-designed barrel cleaning device to evaluate its effectiveness for field-based gun barrel maintenance. The system utilizes a guiding mechanism that holds multiple sandblasting nozzles, whose efficiency directly influences the overall performance of the jet-abrasive installation.

The objective of this study is to conduct an in-depth investigation of the technological parameters of a jet-abrasive system and to determine the time characteristics of the barrel cleaning process for the most widely used artillery systems. To achieve this goal, the following tasks must be addressed:

- to perform numerical and experimental studies of the operational process within the jet-abrasive system across a wide range of parameter values,
- to investigate the custom-designed barrel cleaning device,
- to determine the duration of the barrel cleaning process for the most common artillery systems.

The effectiveness of jet-abrasive barrel cleaning was studied using an experimental-statistical modeling approach, with parameter identification of the mathematical model based on a real physical object.

4 Jet-Abrasive Device for Battlefield Gun Barrel Restoration

4.1 Experimental Stand of the Jet-Abrasive System

The experimental stand for barrel cleaning includes the following components (Fig. 2): a container with sand, a coupling for connecting nozzles (6), binding fittings, and a mobile compressor station. The compressor station has the following parameters: volumetric flow rate of 5.25 m^3/min, maximum discharge pressure of 800 kPa, and a motor power of 40 kW. The station is capable of supplying air to two jet-abrasive units at full capacity. However, to prevent overheating of the motor and switching components of the compressor, it is advisable to adjust the operation of the jet-abrasive system to reduce air consumption and processing time per unit area of the metal surface.

The operation of the stand is as follows: The abrasive material is poured into a sealed container through a sieve 2. Compressed air is supplied through the inlet valve 14 into a tee 9, where a portion of the abrasive material is mixed with air. The amount of abrasive material is regulated by a sand valve 8. The air-abrasive mixture is then delivered through a hose 10 to the nozzle 6.

During the experimental studies, the following parameters are measured: air flow velocity, pressure, temperature, and the amount of abrasive material. The abrasive material used is river sand with a fraction size of 0.5–0.8 mm. The volume of sand in the installation is 0.2 m^3.

This experimental setup allows for the study of the energy efficiency of nozzles with different geometric parameters. The technical parameters of the setup are presented in Tab. 1.

The measurement errors of the actual air and abrasive material flow rates are controlled before the gas flowmeter and directly before the nozzle. To ensure measurement accuracy, the following instruments are used:

- flowmeter “RG 250” with an accuracy class of 1.0 – for controlling the air flow rate,
- strain gauge manometer “D.M. 05-MP-3U” with a maximum pressure of 2 MPa and an accuracy class of 1.5 – for measuring pressure,
- thermometer “Testo 905-T2” – for controlling temperature,
- scales “KS10” with a maximum load of 10 kg and an accuracy of 1 g – for measuring the amount of abrasive.

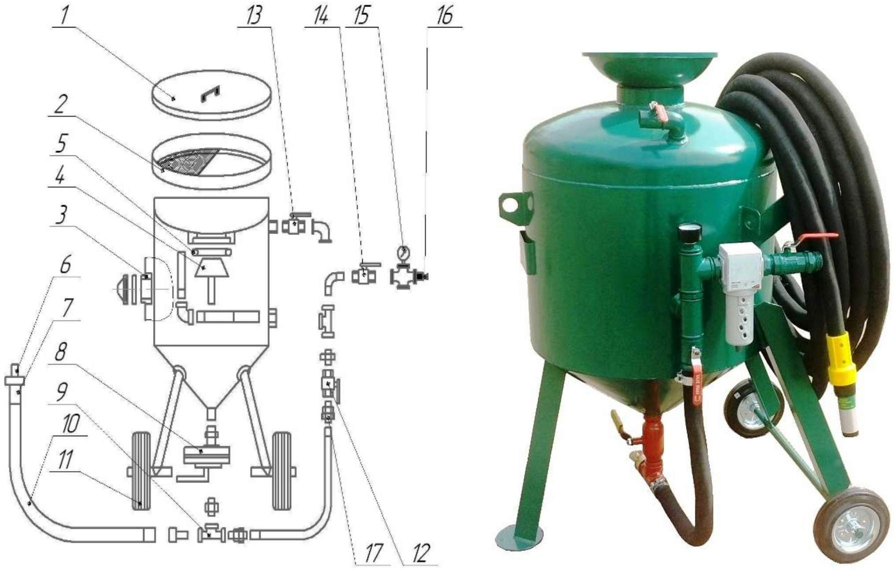

Fig. 2 Scheme and general view of the barrel cleaning installation: 1 – cover; 2 – sieve; 3 – hatch; 4 – closing cone; 5 – closing ring; 6 – abrasive blasting ring; 7 – nozzle holder; 8 – sand gate; 9 – tee; 10 – sleeve; 11 – wheels; 12 – air valve; 13 – drain valve; 14 – inlet valve; 15 – pressure gauge; 16 – air connection; 17 – quick-release connection

Tab. 1 Technical parameters of the experimental setup

N.	Parameter	Unit of measurement	Value
1.	Nozzle length	mm	22
2.	Nozzle diameter	mm	2–20
3.	Inlet mixture pressure	kPa	201
4.	Outlet mixture pressure	kPa	101
5.	Mass flow rate of the mixture	kg/s	0.002–0.24

The measurement error of the main parameter *m* is assessed using the method of indirect measurements [12].

The complexity of processing the inner surfaces of gun barrels using conventional nozzles, which are commonly used in industry, lies in the loss of the reactive force of the jet over the length of its travel and the difficulty in directing the abrasive-air jet to the inner wall at a significant distance from the muzzle. Processing the inner surfaces of short pipes is accompanied by difficulty in achieving uniform processing, especially when there are significant contaminations.

To overcome these problems, we developed several designs of devices for processing the inner surfaces of long tubes (barrels). Additionally, we developed and patented a special device (Fig. 3) that allows the nozzle holder to be moved along the treated surface of the pipe.

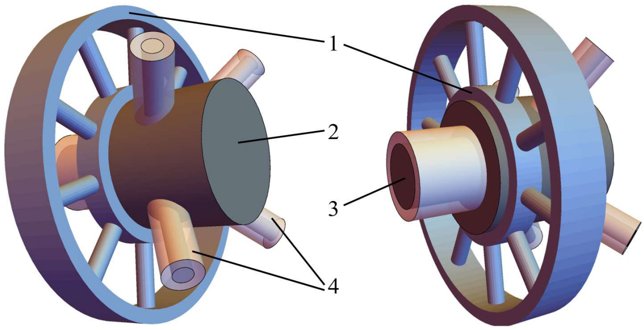

Fig. 3 Device for pneumatic abrasive cleaning of inner surfaces of barrel channels: 1 – movable housing; 2 – guiding apparatus; 3 – connection; 4 – nozzle

This device consists of a guiding apparatus 2, in which several nozzles 4 are installed. The total number of nozzles can vary, but it is important to note that in order to achieve the desired mass flow rate parameters, increasing the number of nozzles requires increasing the pressure at the device's inlet, which the power of the compressor station may limit. The movable housing of device 1 is made of plastic and can be of different diameters, which are selected according to the caliber of the gun barrel.

4.2 Mathematical Foundations of the Barrel Cleaning Process

The further theoretical consideration assumes that the mass of the material removed as a result of abrasive blasting cleaning is approximately equal to the mass of the abrasive material [13].

Of course, this assumption is valid with some reservations. In the simplest approximation, if the process is considered as ideal plastic or brittle fracture, it can be assumed that each abrasive particle with mass m removes an equivalent mass of material from the metal. However, in reality, this process is more complex, and the effectiveness of material removal depends on several factors:

- Angle of incidence of the abrasive particles: At small angles (around 15–30°), mostly erosive wear occurs (removal of thin layers of material). At medium angles (30–60°), the efficiency of material removal is highest. At 90°, the particles mainly create dents, but material removal is less effective.
- Speed of particles (v): High particle speed increases the kinetic energy of the particles, promoting more material removal. However, there is a threshold speed beyond which further speed increases have minimal effect on the effectiveness of material removal.
- Material properties of the metal (hardness, plasticity, brittleness): Brittle materials (e.g., cast iron) are prone to chipping, making the process more effective. Ductile materials (e.g., soft metals like aluminum) are more likely to absorb particle energy through plastic deformation.

- Density and size of particles: Larger particles transfer more energy, resulting in deeper penetration. Smaller particles may remove material more efficiently in thin layers.

The assumption that the mass of the removed metal equals the mass of the abrasive particle is based on the principles of impact fracture and energy balance. This implies that all (or a significant portion of) the kinetic energy of the particle is spent on local material fracture and expulsion of a mass equal to the mass of the particle. Moreover, if it is assumed that the particle removes a portion of the metal in the form of a fragment or chip, whose volume is approximately equal to its volume, the mass of the removed material will be proportional to the mass of the particle.

This assumption works best at high speeds (v > 50 m/s), when the impact energy is sufficient for material chipping, especially for brittle materials such as cast iron, hardened steel, or oxide coatings, and at an optimal angle of incidence (30–60°), where the chipping mechanism is most effective. Therefore, the efficiency of cleaning, and particularly the time required for cleaning, will depend on the mass flow parameters of the abrasive devices.

Let us first examine the mass flow characteristics of a single nozzle. For these conditions, to estimate the mass flow through the nozzle, we will use the fundamental Stodola formula [14]:

$$m = \mu k_a f \sqrt{\frac{\rho_1}{z} \frac{p_1^2 - p_2^2}{p_1}} \tag{1}$$

where m – the nozzle mass flow rate; μ – the nozzle flow rate; k_a – the adiabatic index; f – the nozzle cross-sectional area, [m^2]; ρ_1 – the inlet density, [kg/m^3]; p_1 – the inlet pressure, [Pa]; p_2 – the outlet pressure, [Pa]; z – the number of nozzles (z = 1). Coefficient μ, which takes into account the characteristics of the flow of the abrasive material, is estimated experimentally.

The main geometric parameter that affects the mass flow rate of a nozzle is its internal diameter. To determine the dependence of the theoretical and experimental values of the mass flow rate on the nozzle diameter, several experiments were conducted. As a result of the experiments, we obtain the empirical dependence

$$m(d) = m_{\min} \left(\frac{d}{d_{\min}} \right)^n \tag{2}$$

where d – the nozzle inner diameter, [m]; $d_{\min}$ – the minimum nozzle diameter considered, [m]; $m_{\min}$ – the mass flow rate of the nozzle with the minimum diameter, [kg/s]; n – the regression coefficient.

Fig. 4 shows the experimental m_e and theoretical m_t mass flow rates, respectively. The experimental curve m_e was obtained as a result of research on an experimental stand. The theoretical curve m_t was calculated by Eq. (1). The approximation by Eq. (2) reflects the increase in mass flow rate m with increasing diameter d. The minimum flow rate is observed at minimum values $d_{\min}$: $m(d_{\min}) = m_{\min}$.

Parameters $m_{\min}$ and n are determined from experimental data by minimizing the Mean Square Error (MSE) between the logarithms of the analytical dependence (2) and the experimental data

$$R_m\left(m_{\min},n\right)=\sum_{i=1}^{N}\left\{\ln\left[m_{\min}\left(\frac{d_i}{d_{\min}}\right)^n\right]-\ln m_i\right\}^2\to\min \tag{3}$$

where i – the experimental observation point; N – the total number of observations; m_i– the experimental value of mass flow rate, [kg/s]. Mean Square Error (3) can reach a minimum under the condition:

$$\frac{\partial R_m\left(m_{\min},n\right)}{\partial m_{\min}}=\frac{\partial R_m\left(m_{\min},n\right)}{\partial n}=0 \tag{4}$$

which is related to the following matrix equation:

$$\begin{vmatrix} N & \sum_{i=1}^{N}\ln\frac{d_i}{d_{\min}} \\ \sum_{i=1}^{N}\ln\frac{d_i}{d_{\min}} & \sum_{i=1}^{N}\ln^2\frac{d_i}{d_{\min}} \end{vmatrix}\times\begin{vmatrix}\ln m_{\min}\\ n\end{vmatrix}=\begin{vmatrix}\sum_{i=1}^{N}\ln m_i \\ \sum_{i=1}^{N}\left[\ln m_i\cdot\ln\frac{d_i}{d_{\min}}\right]\end{vmatrix} \tag{5}$$

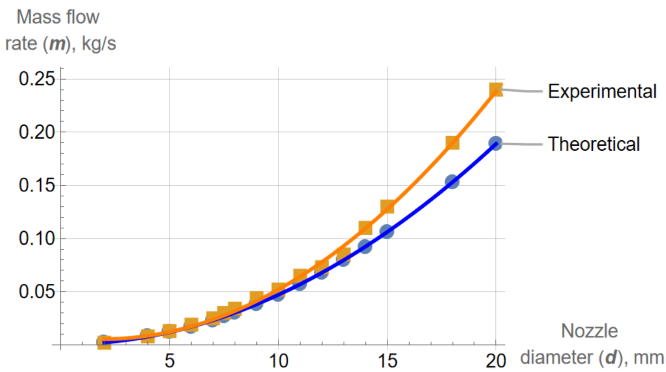

Fig. 4 Dependence of mass flow rate on nozzle diameter

The given parameters can be estimated using the inverse matrix:

$$m_{\min}=\exp\left\{\frac{\sum_{i=1}^{N}\ln m_i\cdot\sum_{i=1}^{N}\ln^2\frac{d_i}{d_{\min}}-\sum_{i=1}^{N}\ln\frac{d_i}{d_{\min}}\cdot\sum_{i=1}^{N}\left(\ln m_i\cdot\ln\frac{d_i}{d_{\min}}\right)}{N\sum_{i=1}^{N}\ln^2\frac{d_i}{d_{\min}}-\left(\sum_{i=1}^{N}\ln\frac{d_i}{d_{\min}}\right)^2}\right\} \tag{6}$$

$$n=\frac{N\sum_{i=1}^{N}\left(\ln m_i\cdot\ln\frac{d_i}{d_{\min}}\right)-\sum_{i=1}^{N}\ln m_i\cdot\sum_{i=1}^{N}\ln\frac{d_i}{d_{\min}}}{N\sum_{i=1}^{N}\ln^2\frac{d_i}{d_{\min}}-\left(\sum_{i=1}^{N}\ln\frac{d_i}{d_{\min}}\right)^2} \tag{7}$$

According to Eqs (6) and (7), the estimated parameters $m_{\min}$ and n are the following: $m_{\min}$ = 0.002 kg/s; n = 2.07 for the case m_e and n = 1.97 – for m_t.

Nozzle flow rate μ also increases the mass flow rate of the nozzle. Therefore, in order to maintain the performance of a worn nozzle, several times more air and abrasive material are required, which increases the overall cost of the AJM. The experimental and theoretical flows differ only slightly, and therefore, a linear approximation of the nozzle flow rate μ can be applied. Fig. 5 shows the dependence of the nozzle flow rate on the internal diameter of the nozzle at a constant pressure difference of 201–101 kPa:

$$\mu(d) = \mu_{\min} + \alpha \cdot (d - d_{\min}) \tag{8}$$

where $\mu_{\min}$ – the flow rate of the minimum diameter nozzle $d_{\min}$; α – the regression coefficient, $[m^{-1}]$.

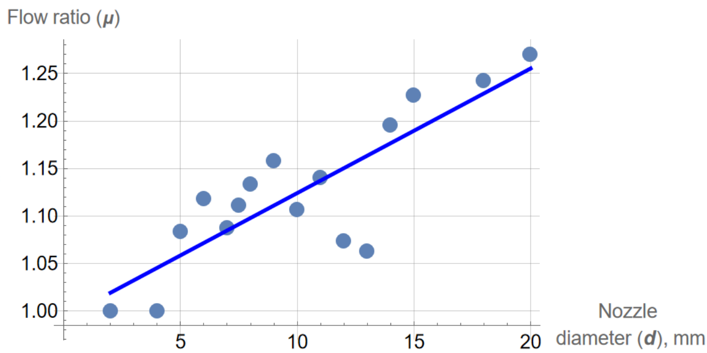

Fig. 5 Dependence of the nozzle flow rate coefficient on its diameter: points – experimental data; line – approximating dependence (8)

By minimizing the MSE, it is possible to estimate the unknown parameters $\mu_{\min}$ and α between the logarithms of the analytical dependence (8) and the experimental data:

$$R_\mu(\mu_{\min}, \alpha) = \sum_{i=1}^{N} (\mu_{\min} + \alpha \cdot \Delta d_i - \mu_i)^2 \rightarrow \min \tag{9}$$

where μ_i – the experimentally obtained flow rate; $\Delta d_i = d_i - d_{\min}$ – the difference between the diameter of the i-th nozzle and the minimum diameter $d_{\min}$, [m].

MSE (9) reaches a minimum under the following conditions:

$$\frac{\partial R_\mu(\mu_{\min}, \alpha)}{\partial \mu_{\min}} = \frac{\partial R_\mu(\mu_{\min}, \alpha)}{\partial \alpha} = 0 \tag{10}$$

which directly corresponds to this matrix equation:

$$\begin{vmatrix} N & \sum_{i=1}^{N} \Delta d_i \\ \sum_{i=1}^{N} \Delta d_i & \sum_{i=1}^{N} \Delta^2 d_i \end{vmatrix} \times \begin{vmatrix} \mu_{\min} \\ \alpha \end{vmatrix} = \begin{vmatrix} \sum_{i=1}^{N} \mu_i \\ \sum_{i=1}^{N} (\mu_i \cdot \Delta d_i) \end{vmatrix} \tag{11}$$

$$\mu_{\min} = \frac{\sum_{i=1}^{N} \mu_i \cdot \sum_{i=1}^{N} \Delta^2 d_i - \sum_{i=1}^{N} \Delta d_i \cdot \sum_{i=1}^{N} (\mu_i \cdot \Delta d_i)}{N \cdot \sum_{i=1}^{N} \Delta^2 d_i - \left(\sum_{i=1}^{N} \Delta d_i \right)^2} \tag{12}$$

$$\alpha = \frac{N \sum_{i=1}^{N} (\mu_i \cdot \Delta d_i) - \sum_{i=1}^{N} \mu_i \cdot \sum_{i=1}^{N} \Delta d_i}{N \sum_{i=1}^{N} \Delta^2 d_i - \left(\sum_{i=1}^{N} \Delta d_i \right)^2} \tag{13}$$

The estimated parameters are $\mu_{\min} = 0.981$ and $\alpha = 16.61$.

The processing performance with one nozzle was also experimentally determined. It significantly depends on the pressure of compressed air. For the study, the following were provided: inlet pressure 201 kPa, outlet pressure 101 kPa, nozzle length 22 mm, inlet density $\rho_1 = 2.4$ kg/m^3. The flow rate depended on the nozzle diameter and could increase due to nozzle wear.

The general geometric and operating parameters of nozzles of different diameters are given in Tab. 2.

Tab. 2 Nozzle geometric and operating parameters

N.	*d* [mm]	*f* [mm^2]	m_e [kg/s]	m_t [kg/s]	μ [–]	c_2 [m/s]
1	2.0	3.142	0.002	0.002	0.981	466
2	4.0	12.566	0.008	0.008	1.060	457
3	5.0	19.635	0.013	0.012	1.060	463
4	6.0	28.274	0.019	0.017	1.119	470
5	7.0	38.465	0.025	0.023	1.082	476
6	7.5	44.156	0.030	0.027	1.131	479
7	8.0	50.240	0.034	0.030	1.126	482
8	9.0	63.585	0.044	0.038	1.152	488
9	10.0	78.500	0.052	0.047	1.103	490
10	11.0	94.985	0.065	0.057	1.139	495
11	12.0	113.040	0.073	0.068	1.075	500
12	13.0	132.665	0.085	0.080	1.066	504
13	14.0	153.860	0.110	0.092	1.190	510
14	15.0	176.625	0.130	0.106	1.225	516
15	18.0	254.340	0.190	0.153	1.243	525
16	20.0	314.000	0.240	0.189	1.272	531

The higher the coefficient μ, the better the nozzle works. This is explained by the fact that the nozzle must pass the maximum amount of abrasive material, giving it the maximum speed. At the same time, with an increase in the nozzle diameter, the compressed air consumption increases significantly, which becomes noticeable, for example, when the nozzle wears out (increases in diameter). Compressed air is a relatively expensive working material, since to ensure the operation of a jet-abrasive machine, a supply of compressed air from 3 to 10 m^3/min is required. To obtain such an amount of compressed air, it is necessary to spend from 30 to 100 kW of electricity. Therefore, the search for more advanced designs of working nozzles of abrasive blasting machines is very relevant, since the air consumption of the machine and the efficiency of the process in general depend on the working nozzle to the greatest extent [12, 14]. Therefore, it is economically inexpedient to carry out surface treatment of materials with worn nozzles or nozzles with an increased internal diameter.

In field conditions, connecting an additional compressor may be impossible due to the limited characteristics of the electrical network. Therefore, choosing nozzles with a larger diameter is not always advisable. Improving the quality of the working process is possible due to the high intensity of turbulence, the presence of recirculation zones, radial redistribution of the total enthalpy, and other properties of the swirling flow.

The above results indicate a significant influence of the geometry of the jet-abrasive nozzle on the technological parameters of the material surface treatment. This must be taken into account when designing and manufacturing jet-abrasive nozzles. Processing time affects the cost of processing, since the jet abrasive device consumes most of the expensive compressed air and abrasive material.

The angle of the mixture profile at the nozzle outlet is constantly changing and depends on many geometric and operational factors. The most influential factors on the angle of the output jet at the nozzle cut are its length, diameter, operating flow rate at the nozzle outlet, the distance between the nozzle and the surface being processed, and the angle of inclination of the nozzle to the surface being processed. The smaller the spray angle, the higher the working mixture velocity and nozzle flow rate we will obtain.

Technological parameters of abrasive blast cleaning of material surfaces are the processing time, the resulting surface roughness, and the values of the operating parameters of the abrasive-air mixture at the nozzle cut. Reducing the fractional structure of the abrasive material leads to a decrease in the roughness of the treated surface. Thus, in practice, it is advisable to adhere to the following recommendations: to remove the contaminated coating, an abrasive with a fraction of 0.2-0.5 mm should be used. A finer fraction of abrasive 0.1-0.2 mm should be used before coating, when corrosion is removed from shells and cavities for finer surface treatment.

In general, based on the integrated application of analytical and experimental methods with computational methods, a comprehensive methodology for designing working nozzles of a pneumatic abrasive installation has been created. The developed approach to assessing the operating parameters of the working nozzle allowed the design of new energy-efficient working nozzles that increase processing efficiency.

4.3 Determining the Time for Barrel Cleaning

Based on the assumption that the mass of the material that is cut off is approximately equal to the mass of the grinding material, we will determine the time which will be needed to clean the gun barrels. For the calculation, we will take a nozzle-grinder of our design with 4 nozzles, 22 mm long and 7 mm in diameter, developed by us. Providing a mass flow rate through one nozzle at the level $m = 0.025$ kg/s, let's investigate the cleaning time of barrels covered with a layer of rust of 1 mm. The density of iron oxide is taken as 5 250 kg/m^3.

As we can see from Tab. 3, the estimated time for cleaning a gun barrel is significantly reduced compared to manual cleaning, which is a fairly influential factor in restoring weapons in the field.

Tab. 3 Estimated time for cleaning barrels from rust 1 mm*, nozzle with* 4 *nozzles with a diameter of* 7 mm

N.	Name of weapons	Caliber [mm]	Barrel length [mm]	Barrel area with rifling [m²]	Rust mass 1 mm layer [kg]	Cleaning time [s]
1	2C9 “Nona-S”	120	2 904	1.204	6.3	63
2	2C1 “Hvozdyka”	122	4 270	1.800	9.5	95
3	Д-30 (2A18)	122	4 785	2.017	10.6	106
4	Tank gun 2A46M	125	6 000	2.356	12.4	124
5	Д-20 (2A33)	152	5 195	2.729	14.3	143
6	2C3 “Akatsiya”	152	6 580	3.456	18.1	181
7	2C19 “Msta-S”	152	7 144	3.753	19.7	197
8	2C5 “Hiatsynt-S”	152	7 144	3.753	19.7	197
9	ShKH vz.77 “Dana”	152	7 904	4.152	21.8	218
10	2A36 “Hiatsynt-B”	152	8 197	4.306	22.6	226
11	M109 (A1-A4)	155	6 000	3.214	16.9	169
12	M109 (A5-A7)	155	6 045	3.238	17.0	170
13	M109A6	155	6 045	3.238	17.0	170
14	M2000 “Zuzana”	155	6 975	3.736	19.6	196
15	AHS “Krab”	155	8 060	4.317	22.7	227
16	CAESAR	155	8 060	4.317	22.7	227
17	PzH 2000	155	8 060	4.317	22.7	227
18	ShKH “Zuzana 2”	155	8 060	4.317	22.7	227
19	2C22 “Bohdana”	155	8 060	4.317	22.7	227
20	2C7 “Pion”	203	11 220	7.871	41.3	413

However, such cleaning requires the availability of appropriate equipment: a jet-abrasive installation, a compressor station, and a set of cleaning nozzles. In addition, Tab. 3 only shows the time for cleaning the barrel from the main layer of rust. This does not include other work that should accompany such cleaning: removal of abrasive material residues and cleaning results from the barrel channel, treatment of the channel with chemicals, cleaning of other parts, lubrication, and other operations.

At the same time, this method ensures quick cleaning of the main part of any gun – its barrel, which ensures quick restoration of equipment without the use of equipment and personnel of repair companies.

The financial aspect of the problem is also important. The cost of jet-abrasive cleaning equipment is \$500–\$1 000. Both stationary and automobile compressors can be used as a source of compressed air. Operation of the installation does not require additional training and can be performed by servicemen of the gun combat service. As shown in [15], the cost of cleaning the barrel of the M256 tank cannon is from \$40 to \$175, depending on the means used. Such an installation can pay for itself after

5-10 barrel cleanings. However, the main advantage of the considered approach is the time, which is several times less than the time of manual cleaning, and the possibility of carrying out such work on cleaning the barrel directly on the battlefield, which significantly increases the combat readiness of artillery units.

5 Conclusions

Intensive combat operations today require field maintenance for a significant number of artillery systems. One of the key factors affecting the condition of the gun barrel is corrosion, which develops due to environmental factors. Restoring guns in combat conditions is a complex task, as it involves numerous operations that require specialized equipment and trained personnel. Consequently, the primary focus of developers is on creating technologies for restoring gun barrels that do not require stationary facilities and that minimize the time spent on these operations.

This study investigated a jet-abrasive installation with a custom-designed barrel cleaning device to assess the feasibility of cleaning gun barrels in field conditions. A guiding device was used as an ejector to hold multiple sandblasting nozzles, with the efficiency of the entire jet-abrasive system depending on its performance.

The results demonstrate a significant impact of the jet-abrasive nozzle geometry on the technological parameters of material surface treatment. Increasing the nozzle diameter also increases the mass flow of the abrasive material. However, this also leads to an increase in the consumption of the air-abrasive mixture, making it economically inefficient to perform surface treatment with nozzles of larger internal diameters.

The use of our specially designed device for processing the inner surface of the barrel allows for the optimization of air-abrasive mixture flow parameters, improves economic efficiency, and significantly accelerates the processing time.

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