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Effect of Erosion on Surface Roughness and Hydromechanical Characteristics of Abrasive-Jet Machining

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Abstract. The article contains the fundamental results of the experimental and numerical investigations for pneumo-abrasive unit nozzles with different geometries. The research was purposed by the pressing need to develop an inexpensive and effective working nozzle design of the air-abrasive unit which can be applied for surface processing before some technological processes are performed, as well as for surface coating, descaling after thermal treatment, processing of hollow holes of the crankshafts, smoothing of the inner surfaces of the narrow channels between the impeller blades after electric discharge machining for ultrahigh-pressure combination compressors. Several designs were considered, ranging from the simplest to those with a complicated inner channel geometry. The impact of the nozzle material and challenging inner surface application on its characteristics has also been studied. The research was done using the application of modern CFD complexes for numerical modeling of the air-abrasive mixture discharge from the working nozzle of the pneumo-abrasive unit. In addition, physical experimentation was provided. The methods applied in the research allow for profound, systematic research of spraying units operating on the air-abrasive mixture within a wide range of geometrical and mode parameters. The novelty of the gained results lies in the development of the mathematical model of the pneumo-abrasive nozzle operating process, the working out of a cheaper nozzle design, getting information about air-abrasive mixture distribution along the nozzle length, giving practical recommendations for calculation and designing a working nozzle for the jet-abrasive unit.

Keywords: abrasive-jet machining, energy efficiency, mathematical model, erosion, surface.

1 Introduction

The conventional nozzle designs of the jet-abrasive unit are relatively expensive. As a nozzle is a costly material, it affects the material processing cost. There is a need to develop a cheaper nozzle design without losing efficiency [1]. Hence, it is necessary to provide a profound investigation of the working nozzle operating process [2]. The key indicator of the nozzle efficiency is the working flow rate at its outlet flow area [3]. The higher it is, the higher its consumption coefficient.

Pneumo-abrasive surface processing is rather energy-consuming [4]. Once a large amount of the compressed air is used in the unit as a carrier flow, a compressor with consumption of 3.5–5.0 m^3/min is needed, from 30 kW to 37 kW. Dry sifted river sand or quartz sand, glass balls, or corundum are used as an abrasive material. As the material processing cost is calculated due to unit operating time, the quality of energy transformation in the power units is of significant importance [5].

Pneumo-abrasive processing permits high-quality processing of any shape and material of engineering parts, elements of structures, and machines during restoration and renovation work [6]. A pneumo-abrasive unit is relatively simple in its design; the main parts affecting its efficiency are a dosing tap and a nozzle, which makes the air-abrasive mixture move [7]. The basic parameters of the jet-abrasive unit nozzle are its geometry, flow area, and length [8].

The higher the flow area value, the higher the compressed air consumption accordingly. The abrasive material application results in the working nozzle wear, increasing the inner diameter, which in turn leads to excessive consumption of compressed air and abrasive material.

Since the working nozzle of the jet-abrasive unit is a costly part that needs replacement from time to time, the cost of the material processing depends on its working efficiency, durability, and price.

As a result, there arises a necessity to develop a new nozzle that can replace currently used nozzles due to a more qualitative transformation of the compressed gas potential energy into kinetic energy of the flowing stream.

2 Literature Review

The nozzles are manufactured from metals and ceramic materials [9, 10]. The list of materials presented below deals only with the nozzle application when they come into contact directly with air and material. The consideration of the basic materials used for nozzles manufacturing, as well as their durability features, has revealed the following lifetime ranges: 1–2 h for ceramic nozzles, 6–8 h for cast iron nozzles, about 300 h for tungsten carbide nozzles, and 750–1000 h for boron-carbide nozzles.

Durability values were calculated for sand. If steel pellets are used, durability increases 2.0–2.5 times.

As for durability, the cheapest solution is the choice of the most durable and hardest nozzles applied for jet-abrasive works despite their high price. Ceramic and cast iron nozzles must not be used for large-scale sandblasting works because their fast wear distorts the general view of the processed surface. Besides, air and material consumption increases considerably if the geometry of the inner surface of the nozzle is not optimal. So, the production costs per one square meter of the processed surface rise considerably.

The nozzle made of tungsten carbide can be used for all the applied materials [11]. The nozzles faced with Bor carbide can be used for any material. The disadvantage of these nozzles is their high price, about 200 EUR.

To evaluate the impact of the nozzle's inner surface quality and flow part geometry on its characteristics, it is necessary to investigate the air-abrasive mixture discharge working process and analyze the literature on the point.

In the paper [12], the authors identified a high-frequency pressure component in the throttling device resulting from the nonlinearity of the hydromechanical system. The results show a pressure decrease in the end channel, contributing to a better understanding of the gas-dynamic stream flow through throttles.

In the paper [13], the study of the hydrodynamics of the two-phase output flow in the prismatic units with a variable cross-section was performed. The flow friction coefficient was identified analytically, and mathematical modeling of the gas-dispersed flow in the vertical pneumatic classifier was developed.

In the paper [14], the characteristics of the ejector in the vortex chamber for pumping over bulk medium were found. The mathematical model's adequacy was based on comparing the flow integral characteristics: mass consumption and pressure in all gas channels and mass consumption of the bulk medium in the inlet and output channels. The flow rate of the solid particles at unit output correlates with the solid particles' diameter. The rational size of the solid particles, which must ensure maximum granular medium consumption due to their minimal standing in the vortex chamber, was identified.

In the paper [15], the study of the gas-dynamic two-phase evaporation in the prismatic units with a variable section was performed. The author developed a mathematical gas flow model based on the turbulent flow averaged in time and space and supplemented it with the study of the solid particle flow. The dependencies needed for velocity field identification of solid particles in the pneumatic classifier and friction coefficient identification were gained, and the equations for identification of the velocity field of the gas phase using the velocity components of the two-dimensional gas flow were developed.

The paper [16] modeled the aerodynamics of the two phases of the nonisothermal turbulent flow in the vortex chamber in the air centrifugal classifier. Based on the Wilcoxon turbulent model, the Reynolds equations calculated the gas phase dynamics with their closing. The movement of the solid phase of ultradispersed powder was modeled by the combination of the calculations of particular particle trajectories due to the Lagrange coordinate system. The impact of turbulent diffusion of the particles and other factors on the efficiency of particle segregation by their size is shown. The reliability of the results was proved by the tests and by comparing the numerical results with the already-known experimental data.

The paper [17] applies the random vortex method (RVM), which is the Lagrange approach to the bubble trajectory modeling in the two-phase bubble flow around the circular cylinder. The main advantage of this approach is its ability to model turbulence directly. With RVM, the turbulence is modeled by the solution of the vortex transfer equation, and there is no need to apply the closing model to it. Another advantage of RVM, compared with the other CFD approaches, is its independence in mesh generation. The results showed that the Reynolds number increase leads to a decrease in the bubble's rising speed.

A similar picture can be seen for the bubbles with smaller diameters. Due to the analyzed data, the actual Lagrange-Lagrange model can solve the mesh generation problems and turbulence modeling presented in the general diagrams of the two-phase modeling.

The paper [18] is devoted to the optimal choice of the division limit values. The equipment used allows for obtaining the standard granulometric composition of sand. The mathematical model for pneumatic classifiers optimized work was developed.

The paper [19] presents the change analysis of the interfacial surface and the drop sizes formed in the spray tower. The interfacial surface and the drop size are essential for the equipment's efficiency in terms of pressure losses and process efficiency. The microphotography technology measures the size of the liquid film and drops. Conventional confusors were considered with the profiled inner and double-profiled inner surfaces. The dimensionless correlation for the reduced Saude average diameter was proposed.

The paper [20] considers methods dealing with aerodynamic modeling of the two-phase turbulent vortex flow in the pneumatic centrifugal classifier's separate chamber. The speed field for the turbulent vortex flow of the gas phase is determined based on the Reynolds equations closed with the Wilcox two-parameters turbulence model. The movement of the fine solid phase is modeled by calculating the trajectories of particular particles in the Lagrange coordinate system considering inertial, centrifugal, gravitational, and aerodynamic forces. A semiempirical probabilistic model provides the effect of the turbulent dispersion of the particles caused by the gas phase pulsating movement. Numerous calculations have shown that consideration of this phenomenon strongly influences particle separation.

The influence of operating parameters on the aerodynamics and fine particle separation in the pneumatic centrifugal classifier was also analyzed.

Applying various hydrodynamic resistance methods to the working fluid in the rotary machines [21] makes it possible to increase processing efficiency to get fine homogeneous mixtures with the proper characteristics. This article is devoted to investigating liquid flow formation in the work zone of the rotary cavitation activator and to determining the basic principles of energy impact.

3 Research Methodology

3.1 The mathematical model

A plane flow of an air-abrasive mixture with particles of average diameter d is considered (Figure 1).

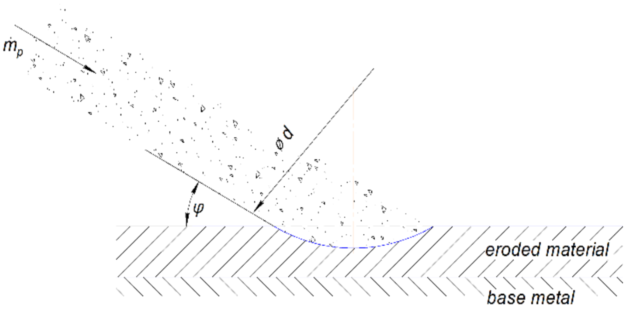


Figure 1 – The design scheme for mathematical modeling

The interaction of the jet with the metal surface at an angle φ leads to erosion of the surface with a depth of Δ:

$$S = \frac{1}{8} d^2 [\varphi - \sin(\varphi)]. \tag{1}$$

The particle of the thickness b is as follows:

$$m_0 = \rho S b, \tag{2}$$

where ρ – density of the eroded material, kg/m^3.

After considering the relationship

$$\cos(\varphi) = 1 - 2\frac{\Delta}{d}, \tag{3}$$

the following trigonotetric dependency can be written:

$$\begin{aligned} \sin(\varphi) &= 2\cos\left(\frac{\varphi}{2}\right)\sqrt{1-\cos^2\left(\frac{\varphi}{2}\right)} = \\ &= 4\left(1 - 2\frac{\Delta}{d}\right)\sqrt{\left(1-\frac{\Delta}{d}\right)\frac{\Delta}{d}}. \end{aligned} \tag{4}$$

Due to a relative smallness of erosion depth compared with particle size (Δ << d), after considering the Maclaurin expansion of the function (4) in terms of the angle φ, the dependence (1) takes the following form:

$$S = \frac{4}{3}\Delta^{\frac{2}{3}}\sqrt{d} + O\left[\left(\frac{\Delta}{\mathrm{d}}\right)^2\right], \tag{5}$$

where O – higher-order terms.

Therefore, the expression (2) is as follows:

$$m_0 = \frac{4}{3}\rho b \Delta^{\frac{2}{3}}\sqrt{d}, \tag{6}$$

from which the depth can be obtained:

$$\Delta = \left(\frac{3}{4}\frac{m_0}{\rho b\sqrt{d}}\right)^{\frac{2}{3}}. \tag{7}$$

After differentiating the both parts in terms of time t,

$$\frac{\mathrm{d}\Delta}{\mathrm{d}t} = \frac{\mathrm{d}\left(\frac{3}{4}\frac{m_0}{\rho b\sqrt{d}}\right)^{\frac{2}{3}}}{\mathrm{d}t} = \frac{\frac{2}{3}\frac{\mathrm{d}m_0}{\mathrm{d}t}}{\left(\frac{4}{3}\rho b\Delta^{\frac{2}{3}}\sqrt{m_0 d}\right)^{\frac{2}{3}}} \tag{8}$$

and considering the expression (6), the following equation can be obtained:

$$\frac{\mathrm{d}\Delta}{\mathrm{d}t} = \frac{\frac{\mathrm{d}m_0}{\mathrm{d}t}}{2\rho b\sqrt{\Delta d}}. \tag{9}$$

Introducing the erosion intensity, m/s:

$$v = \frac{\mathrm{d}\Delta}{\mathrm{d}t} \tag{10}$$

and under the assumption that it is proportional to the mass flow rate of the particles:

$$\frac{\mathrm{d}m_0}{\mathrm{d}t} = K\dot{m}_p, \tag{11}$$

where K – dimensionless parameter, the following expression can be obtained:

$$v = \frac{K\dot{m}_p}{2\rho b\sqrt{\Delta d}}. \tag{12}$$

After extrapolating this dependence to a general case of the spherical particles, the following expression can be proposed:

$$v_e = \frac{K_e}{\sqrt{\Delta}}\frac{\dot{m}_p}{2\rho d_S^{\frac{3}{2}}}, \tag{13}$$

where d_S – Sauter mean diameter, m; K_e – dimensionless parameter that considers both the particle shape and erosion intensity.

Evaluation of the parameter K_e can be realized using the minimization of the following mean square error:

$$R(K_e) = \sum_{i=1}^{N} \left(\frac{K_e}{\sqrt{\Delta_i}} \frac{\dot{m}_p}{2\rho d_S^{\frac{3}{2}}} - v_e^{<i>} \right)^2 \rightarrow min, \quad (14)$$

where n – the total number of experimental data; i – experimental point (i = 1, 2, …, n).

After introducing the parameter that does not influenced on the experimental point

$$\Lambda = \frac{\dot{m}_p}{2\rho d_S^{\frac{3}{2}}}, \quad (15)$$

the condition for minimizing the functional (14)

$$\frac{\mathrm{d}R(K_e)}{\mathrm{d}K_e} = 2\sum_{i=1}^{N} \left(\frac{K_e \Lambda}{\sqrt{\Delta_i}} - v_e^{<i>} \right) \frac{1}{\sqrt{\Delta_i}} = 0 \quad (16)$$

allows for evaluating the unknown parameter:

$$K_e = \frac{1}{\Lambda} \frac{\sum_{i=1}^{N} \left(\frac{v_i}{\sqrt{\Delta_i}} \right)}{\sum_{i=1}^{N} \left(\frac{1}{\Delta_i} \right)}, \quad (17)$$

3.2 The experimental research methodology

The prototype of the working nozzle of the pneumo-abrasive ejector unit is being investigated within a wide range of geometrical and operating parameters.

While testing, the air will be used as a carrier flow, and the river sand with a grain of about 0.30–0.55 mm, irregular shape, with a density of 1500–1700 kg/m^3 and melting temperature of 1728 °C, is used as an abrasive material.

The prototype list of the working nozzles of the pneumo-abrasive ejector unit includes a cylindrical nozzle, a Venturi nozzle, an industrial nozzle UDC32-450, and a hard surface nozzle.

The operating parameters of the prototype unit work are within the following ranges: inlet gas pressure in the jet-abrasive unit – 0.2–0.8 MPa; output gas pressure – 0.1–0.6 MPa; inlet gas temperature – 283–303 K; air consumption – not more than 5.25 m^3/min.

The design scheme of the experimental stand is presented in Figure 2.

The basic components of the stand for a pneumo-abrasive ejector unit are a sand-jet device, a compressed air source, strapping and shut-off valves, a nozzle holder, a nozzle, and a dynamometer board.

The pneumo-abrasive ejector unit is designed to provide mechanical work on the processed surface by conversion of the excess pressure energy of the air-abrasive mixture at the working nozzle discharge point.

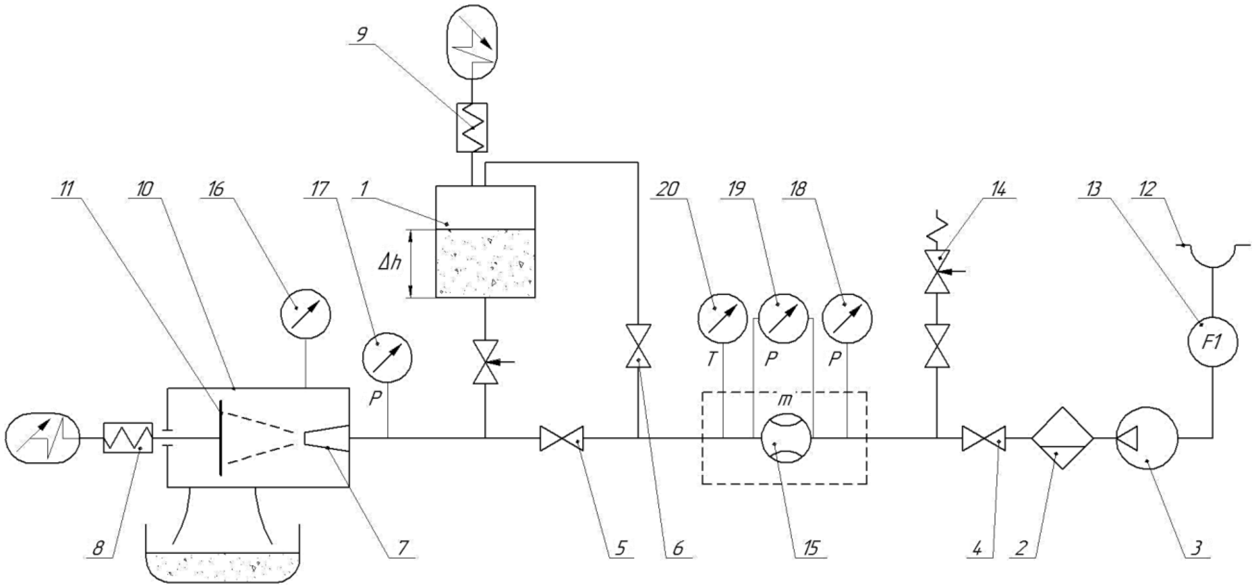


Figure 2 – The design scheme of the experimental stand: 1 – tank with abrasive material; 2 – dehumidifier; 3 – compressor; 4–6 – shut-off valves, 7 – nozzle; 8 – dynamometer; 9 – electronic scales; 10 – jet reaction measuring device; 11 – load plate; 12 – air intake; 13 – air consumption measuring device; 14 – safety valve; 15 – measuring washer; 16–19 - pressure gauges

The abrasive material (namely the river sand with a grain diameter of 0.5 mm) is poured into tank 1, which is hung to the cathead using the crane scales OCS-0.5-X2L with the average accuracy class. The air used as a carrier flow enters the unit through the air intake12 and is driven by compressor 3 partly to the tank with abrasive material through the dehumidifier 2 and shut-off valves 4–6, partly to the nozzle 7 through the trunk rubber sleeve where the air-abrasive mixture is accelerated to the proper working velocity. The working air-abrasive flow strikes load plate 11 connected to dynamometer 8, which measures the load force on load plate 11.

The stand is also equipped with a measuring washer 15 through which the pressure drops at gauges 18 and 19 are measured, and therefore, the air consumption through nozzle 7 can be determined. Gauges 16 and 17 allow for determining the pressure losses caused by the hydraulic resistance of the fittings of the unit. The carrier phase temperature is controlled by the thermometer 20. If excess pressure appears in the unit, it is relieved to the operating values of valve 14.

Thus, the following parameters are measured: air consumption, m^3/min; abrasive material consumption, kg/min; air pressure, MPa; air temperature, °C; barometric pressure, mmHg; air-abrasive jet pressure on the load plate, kg. The relative errors of the direct and indirect measurements range within 5–7 %, which are admissible.

Before starting the pneumo-abrasive unit, it is necessary to drain condensate from the receivers. After that, the compressor is started. The shut-off valves 4–6 are opened after the unit enters its stationary operating mode. In 1–2 minutes, the required abrasive material supply is adjusted with the control valve, and then the unit is ready to process the surfaces of the parts. To stop the unit, it is primarily necessary to shut off the supply of the abrasive material; then, the compressor is stopped.

3.3 Numerical simulation approach

The drawing of the nozzle is presented in Figure 3.

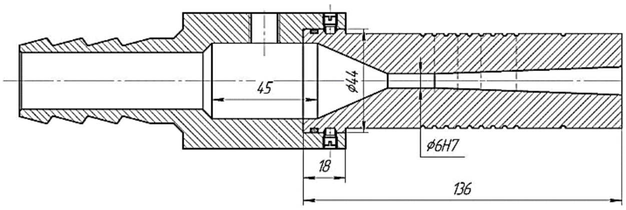


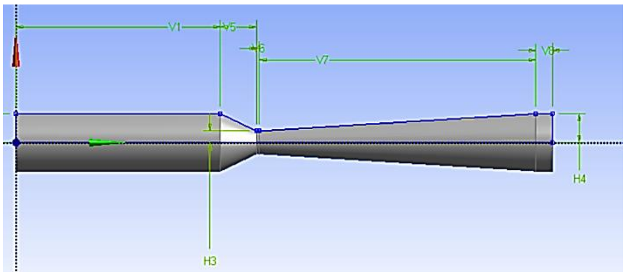
Figure 3 – Drawing of the working nozzle

3D modeling using Autodesk and numerical simulation using ANSYS were based on the following algorithm (Figure 4): building a 3D model of the nozzle UDC32-45, designing the computational mesh with the total number of elements of about $2.5 \cdot 10^5$, selection of calculation settings, setting boundary conditions, visualization of the air-abrasive mixture flow, and the analysis of the obtained results.

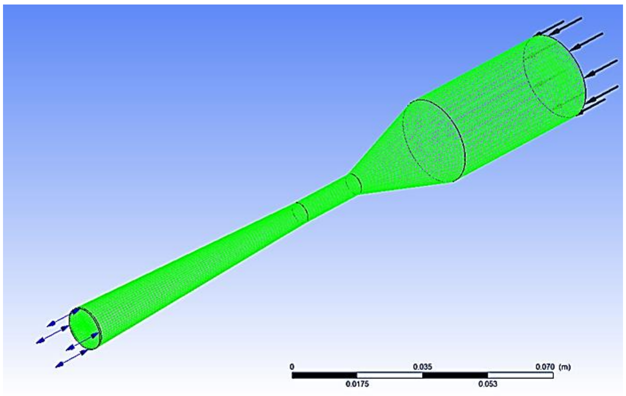
Two media were selected: fluid for air and particle for sand grains with a preset diameter of 0.5 mm and various mass flow rates.

For the fluid model, the turbulence was SST model. For the particle model, the particle mass flow was set. For the fluid model, the total pressure and temperature at the inlet and the pressure at the output were set. The wall roughness was set as 3.2 µm.

The air has the property of state leveling. The density of sand grains and their diameter were preset. While providing a numerical investigation, the heat exchange between sand, air, and nozzle walls was not considered; the abrasive material had one diameter value for sand grain balls of the same diameter.



a

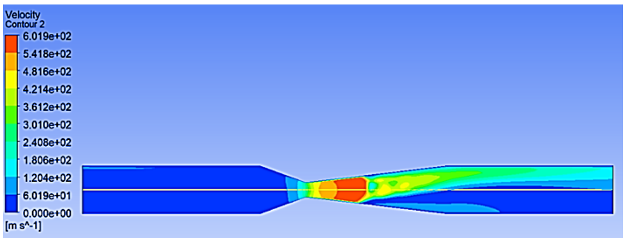


b

Figure 4 – 3D model (a) and the boundary conditions (b)

4 Results

As a result of experimental and numerical simulation and analytical studies, the jet reaction force was evaluated for basic parameters of the Venturi nozzle with different critical diameters and lengths (Figures 5–7).



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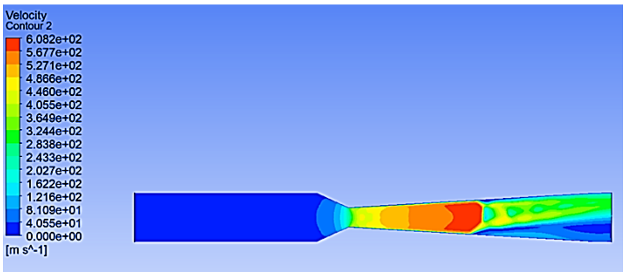
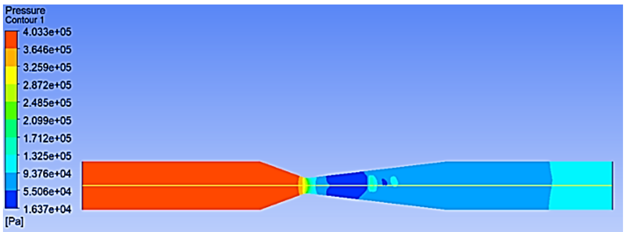


b

Figure 5 – The velocity field, m/s: a – critical diameter of 4 mm and length of 143 mm; b – critical diameter of 8 mm and length of 194 mm



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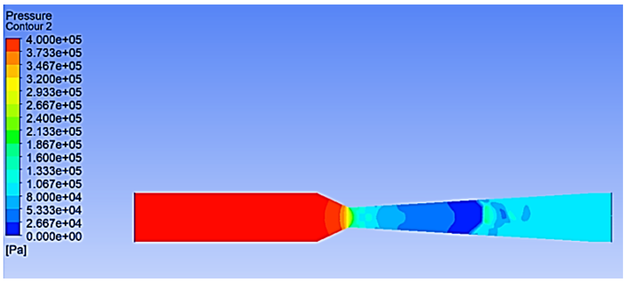
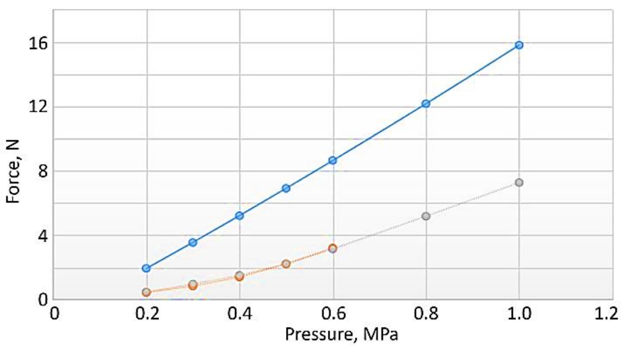


b

Figure 6 – The pressure field, Pa: a – critical diameter of 4 mm and length of 143 mm; b – critical diameter of 8 mm and length of 194 mm



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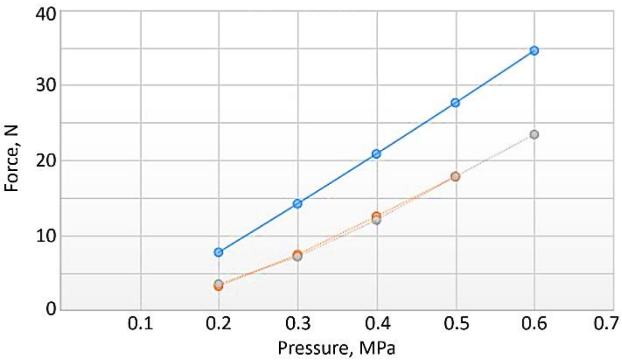

b

Figure 7 – Impact of pressure difference on jet reaction force: a – critical diameter of 4 mm and length of 143 mm; b – critical diameter of 8 mm and length of 194 mm (red – experimental values; grey – polynomial approximation; blue – analytical evaluation)

Overall, the experimental results on the impact of the surface roughness on pressure difference for different sand fraction compositions are summarized in Figure 8.

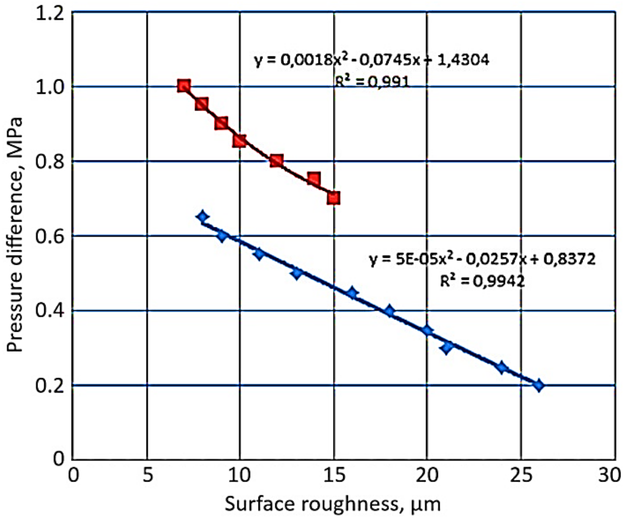

Figure 8 – Surface roughness vs. pressure difference for different fraction composition of sand: blue – 0.1–0.2 mm; red – 0.2–0.5 mm

The diagrams illustrate that fine fraction sand application results in a higher quality surface due to a larger contact area of the abrasive material with a processed surface. It also allows for obtaining the dependencies of the operating pressure difference on the processed surface roughness.

5 Discussion

The obtained results made it evident that surface roughness affects nozzle characteristics significantly. The function of the nozzle of a pneumo-abrasive unit is to accelerate the air-abrasive mixture to its limit [22, 23]. Individual features of a particular nozzle cause this velocity limit.

Each nozzle has a different capacity, so it has its individual consumption coefficient value. The higher the consumption coefficient value of a nozzle, the higher the air-abrasive mixture’s mass consumption value. An ideal nozzle has the highest possible air-abrasive mixture consumption at the highest possible velocity. Many operating features lead to the reduction of the velocity value at the nozzle cut, mainly insufficient pressure drop before and after the nozzle and excessive nozzle length, which slows down the working mixture due to friction, roughness, and wear of the nozzle inner surface, non-stationary abrasive material supply, and others.

If the acceleration at the nozzle output is not high enough, the quality decreases, and the material processing time increases. Thus, to improve nozzle performance, it is necessary to provide its inner surface roughness, which is not easy under actual conditions because the nozzle operates the abrasive material. Our studies validated that there is a more accessible and effective way to overcome the nozzle hydraulic resistance, namely, its reduction in length.

Notably, reducing the length of the nozzle with a variable cross-section can result in the loss of its gas-dynamic advantages over other, more straightforward designs. Therefore, our further studies will focus on optimizing the flow part of this nozzle type. Choosing a more durable coating that can resist wear for longer is also necessary.

The fact of obtaining velocity values of the air-abrasive mixture at the nozzle output corresponding to supersonic flow mode appeared to be quite interesting because it seems impossible if viewed as air leakage from a cylindrical nozzle since supersonic speed can be obtained only in the variable section nozzle, i. e., both confusor and diffusor parts are combined. This phenomenon was explained using CFD visualizations: a vacuum zone inside the nozzle was found, caused by a natural pressure drop and flow rate increase. Thus, at the nozzle exit, low-pressure working flow meets a higher atmospheric pressure, forming a flowing stream imitating a diffusor part of the nozzle. This provokes a sharp increase in pressure. This phenomenon also explains the efficiency of the simple shortened cylindrical nozzle.

6 Conclusions

An experimental stand was developed to investigate the discharge of the air-abrasive mixture from the working nozzle of the pneumo-abrasive unit.

The technique of modeling the discharge of the air-abrasive mixture from the working nozzles with different geometry within an extensive pressure range was practiced.

Differences in velocity values were determined at the output of the cylindrical nozzles manufactured from ceramics and metal (up to 10 %), which testifies to velocity losses due to differences in the inner surface of the nozzle.

The length reduction of the cylindrical steel nozzle from 22 mm to 11 mm resulted in a velocity increase of the air-abrasive mixture in the exit section up to 60 %.

A cylindrical nozzle with a diameter of 4.5 mm, manufactured from the ceramic insert, processes 1 m^2 by 70 % faster than with a similar nozzle of the same size.

Nitriding of the steel nozzle's inner surface increases its lifetime from 10 h to 50 h.

If wall roughness is 3.2 μm, the reduction in traction in the nozzle UDC32-450 (the critical diameter is 6 mm) makes 14 %.

The impact of the roughness of the nozzle's inner surface on its efficiency was determined. Overall, surface roughness contributes to reduction in discharge velocity of the air-abrasive mixture by 10 % compared with a hydraulic smooth nozzle and increases surface processing time.

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