This work investigates the process of powder particle acceleration in a supersonic nozzle for cold gas-dynamic spraying (CGS). The task addressed in the study is predetermined by the lack of established patterns in the comprehensive influence of gas parameters and nozzle geometry on the speed of powder particles at the nozzle outlet, which complicates predicting and controlling the spraying process.

A new approach to the design of nozzles for CGS has been proposed and implemented, which allows for targeted optimization of their geometric parameters taking into account the gas parameters at the nozzle inlet. The approach is based on a combination of analytical modeling (isentropic model, particle acceleration model), methods of statistical planning and analysis of experiments (central compositional design, construction of regression equations), and multifactor optimization of nozzle geometry.

Regularities have been established between the velocity of aluminum particles with a size of 25 µm at the nozzle outlet and the gas parameters: stagnation pressure 0.8–2.5 MPa and stagnation temperature 300–700°C. The calculations also took into account the influence of the nozzle geometry: critical diameter 1.0–3.0 mm, outlet diameter 5.0–10.0 mm, length of the expansion section 80–150 mm. The resulting nozzle and spraying mode ensure that the particles achieve a velocity at the outlet of 596 m/s, which exceeds the required minimum of 550 m/s, at an air flow rate of 1.0 m^3/min.

The proposed approach could be applied to designing new nozzles for mobile and stationary CGS installations operating on compressed air, nitrogen, or helium with a pressure of 0.6 to 4.0 MPa; in particular, for spraying protective and restorative coatings under conditions of limited gas flow. The results lay out the foundation for developing a software tool or an automated system for designing nozzles for CGS in a wide range of initial gas and powder parameters

Keywords: isentropic model, particle acceleration, multifactor optimization, critical speed, analysis of variance

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DEVISING AN APPROACH TO CALCULATING AND OPTIMIZING A SUPERSONIC NOZZLE FOR COLD GAS-DYNAMIC SPRAYING

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1. Introduction

Cold gas dynamic spraying (CGS) is an advanced and promising method for applying protective and restorative coatings. The process involves accelerating and heating powder particles with a heated compressed gas flow using a supersonic nozzle, which, upon contact with the surface, are plastically deformed with the formation of adhesive bonds.

A generalized scheme of the CGS process, the main components and parameters are shown in Fig. 1.

A feature of the process that distinguishes CGS from other gas thermal spraying methods is the absence of melting of powder particles, i.e., the particles in the process of coating formation are in a solid state. This allows coating thin-walled parts made of aluminum, magnesium, and titanium alloys that are sensitive to temperature without structural and phase transformations in the coating materials and the base material.

The most common for use in accelerating the gas flow and powder to supersonic speeds is the Laval constriction-expansion nozzle. The efficiency of the process and the quality of the coatings depend on the spraying modes and to a large extent on the nozzle geometry. Nozzle parameters such as length, expansion angle, and critical cross-sectional area (together with the pressure and temperature of the gas at the inlet) determine the kinetic energy of the particles and their temperature.

The topic of research on the optimization of supersonic nozzles and parameters of the spraying process is important for revealing the full potential of CGS technology. This is the basis for obtaining coatings with high quality indicators at minimal cost for various industrial applications. Therefore, it is a relevant task to carry out studies on the design of supersonic nozzles for spraying.

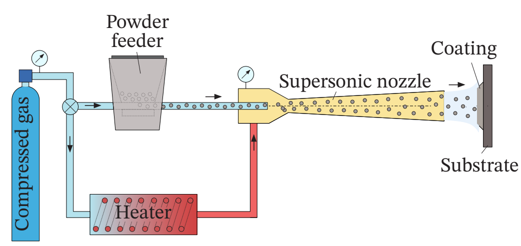

Fig. 1. Schematic representation of the cold gas dynamic spraying process

2. Literature review and problem statement

The results of optimizing the nozzle geometry by varying the expansion angle and the length of the expansion part that were reported in [1] made it possible to increase the particle velocity. In [2], it was demonstrated that changing the length of the expansion part of the nozzle generates a supersonic flow in which the particles receive sufficient energy to form adhesion with the substrate. The authors of [3] took a slightly different path and focused on how the modified nozzle shapes affect the focusing of the particle flow – this allowed them to improve the coating density. In [4], the nozzle was optimized by the angle of entry of particles into the main flow, which reduced the turbulence of the flow. However, issues related to the assessment of the comprehensive influence of geometric parameters on the temperature-velocity characteristics of the gas flow and powder remain unresolved. The reason is that the above works mainly use single-factor studies. As a result, the results do not allow us to assess the nonlinear effects of the interaction between the studied variable factors.

Computer modeling is used not only to determine the dependences of acceleration and heating of particles in nozzles of various geometries but also to find the optimal gas parameters for this purpose for particles to achieve critical velocity values. In recent years, numerous new studies have expanded the understanding of the nozzle optimization procedure and the CGS process as a whole.

The parameters of aluminum and copper particle spraying were optimized using the response surface methodology in [5]. Experimental verification of the results showed that the error in predicting the particle velocity is less than 2%. The authors of [6] validated the results of computational gas dynamics of the flow with powder particles in the nozzle by comparing them with the results of the particle flow visualization method. The effect of gas temperature on the characteristics of coatings is shown by the authors of [7] for optimizing the spraying modes of aluminum-based coatings. The results of theoretical studies reported in [8] emphasize the importance of taking into account the flow and particle parameters for improving the spraying processes and improving the properties of coatings. In the above works, the optimization of modes was carried out for specific nozzles, the geometry of which did not change, and the issue of identifying the patterns of the influence of nozzle sizes on particle velocity was left out of consideration.

The morphology of the powder particles should also be taken into account when studying the gas dynamics of a two-phase flow in a nozzle. It has been established that particles of irregular shape give better kinematic characteristics, which is explained by higher values of the drag coefficient [9].

Currently, in the practice of CGS, nozzles with powder feed into the subsonic and supersonic parts of the nozzle are used. In [10], an ejector nozzle for copper spraying was designed, which increased the efficiency of the process and the adhesion strength of the coatings. The shape of the nozzle and the point of powder introduction play an important role not only in ensuring high particle velocities at the nozzle outlet but also in ensuring the cost-effectiveness of the process [11]. The diameter of the critical section of the nozzle affects the gas flow characteristics through the nozzle. In [12], the acceleration of particles of different diameters in a low-pressure cold spraying nozzle was studied using computational gas dynamics to describe the behavior of particles during spraying of a composite powder mixture. Such modeling allows us to simultaneously study the acceleration of particles of different powders, while the use of analytical models allows us to do this in turn. At the same time, computer simulation requires significant computational resources and time to calculate each individual geometry option. The resource intensity of a single computer calculation often turns out to be impractical, especially for solving complex optimization problems where it is necessary to search for the optimal option from thousands of nozzle geometry options.

If we look at related problems, then in the context of computational gas dynamics, nozzle design, and multifactor optimization, there is always interest in aerodynamic profiles. For example, in [13], a method for optimizing blades for small wind turbines was presented, which combined computational gas dynamics, response surfaces, and a gradient-free optimization method. This approach has the potential to be adapted to the design problems of CGS nozzles. In [14], the results of modeling a two-phase flow (air + solid particles) around the wing of an unmanned aerial vehicle were shown. The study used a discrete phase Euler-Lagrange model, which provides valuable ideas for analyzing the interaction of particles with the flow in a CGS nozzle. However, adaptation of the described methods for CGS nozzles is required, since the flow for the latter case is considered compressible with the presence of seal jumps in the middle of the nozzle channel.

All this emphasizes the important role of nozzle geometry for CGS and shows that even minor variations in shape can significantly affect the quality of the coating. These findings are crucial for improving the design of equipment and improving the efficiency of the process. Achieving these goals requires the development of nozzle optimization methods and finding optimal parameters of the CGS process, based on computer modeling, machine learning, experimental methods, etc.

But, despite a significant amount of work on nozzle modeling and development, the vast majority of existing design methods still rely on somewhat simplified or isolated approaches. Either this is pure flow analytics, or separate computational gas dynamics (often without proper experimental validation), or generally empirical geometry selection. It is clear that such an approach greatly complicates the design and optimization of a nozzle that would meet all the key conditions at the same time: achieving critical velocity values by powder particles, flow stability, gas flow limitations.

In addition, most studies focus on optimizing the spraying parameters (gas parameters, powder characteristics, etc.) for a specific existing nozzle, outside the context of a comprehensive nozzle design that takes into account the full physics of particle acceleration. Therefore, optimization often seems to lack deep integration between nozzle geometry, gas parameters, and momentum transfer mechanisms.

All this suggests that there is a need for a new approach that would integrate multiple levels of modeling, statistical design of experiments, and rigorous validation within a single nozzle design algorithm. Modern approaches that combine experimental methods, numerical modeling, and artificial intelligence algorithms open up new opportunities to improve process efficiency and ensure high coating quality.

3. The aim and objectives of the study

The aim of our study is to devise a new approach for calculating and optimizing the geometry of nozzles for CGS by combining analytical, statistical, and numerical modeling methods. This will make it possible to ensure the required powder particle velocity and gas flow stability at the nozzle outlet in order to form high-quality coatings.

To achieve the goal, the following tasks were set:

– to propose a structure for the nozzle design approach;

– to calculate the velocity of aluminum powder particles at the nozzle outlet depending on the selected initial parameters with an assessment of their influence using variance analysis and building a regression equation;

– to optimize the studied factors to ensure the required powder particle velocity at the nozzle outlet for spraying, taking into account the specified gas flow rate through the nozzle.

4. The study materials and methods

4. 1. The object and hypothesis of the study

The object of our study is the process of powder particle acceleration in a supersonic nozzle for CGS.

The main idea of the proposed approach to nozzle design is to combine analytical and statistical methods into a single, logically consistent cycle with the possibility of targeted multifactorial geometry optimization based on significant spraying parameters. The principal hypothesis assumes the possibility of ensuring high accuracy of prediction ($R^2 > 0.9$) of the velocity of powder particles at the nozzle outlet at the stage of its design. In this case, the nozzle geometry and gas flow parameters at the inlet are taken into account.

The research methodology is interdisciplinary, combines the principles of gas dynamics of two-phase flows, applied mathematics, and statistical analysis. It is based on a combination of analytical, statistical, and numerical methods to solve the scientific and applied problem of rational design and optimization of nozzle geometry for CGS. The proposed methodology makes it possible to take into account the relationships between nozzle geometry, flow parameters, and particle acceleration dynamics. This provides a basis for multifactor optimization with objective functions.

4. 2. Analytical modeling

The key in the process of calculating and optimizing supersonic nozzles for CGS is the calculation of the flow parameters in the nozzle. For this purpose, basic gas-dynamic equations describing the flow in the nozzle can be used. A one-dimensional isentropic gas-dynamic model is known, which describes an ideal compressible flow in the nozzle channel [15]. This model was used in our study to calculate the particle velocity in the nozzle.

Given the gas parameters at the nozzle inlet (pressure, temperature, etc.), as well as the nozzle geometry (length, critical diameter, expansion angle, etc.), the gas velocity, temperature, pressure, and density in any nozzle cross-section can be determined. The following simplifications are adopted in the calculations [16–18]:

– the flow is considered one-dimensional, in which the nozzle cross-section A_0, gas pressure P_g, gas velocity v_g, and gas density ρ_g vary along the straight X-axis;

– the flow is adiabatic (without heat transfer) and frictionless. The model does not take into account the presence of a boundary layer on the inner walls of the nozzle;

– the gas is described by the laws for an ideal gas.

To calculate the convergent part of the nozzle, a method based on geometric relations and gas-dynamic dependences of the flow in the subsonic and supersonic parts of the nozzle was used [19]. The initial data for the calculation is the ratio of the nozzle length to its exit diameter. Knowing this ratio and the expansion angle, it is possible to calculate the nozzle length and the entrance diameter, which is sufficient for the complete construction of the channel geometry. Based on the established area of the entrance cross section, it is possible to calculate the mass flow rate of gas through the nozzle.

4. 3. Mathematical experimental design, statistical analysis, and multifactor optimization

To study the influence of nozzle geometry and flow parameters on the particle velocity at the nozzle exit, mathematical experimental design was applied in combination with statistical analysis of the obtained results. This makes it possible to minimize the number of experiments while maintaining the accuracy of analytical dependences between the input parameters and the objective function.

The work uses the response surface methodology to build an experimental plan, determine the influence of individual factors and their interaction on the objective function and optimize according to established criteria. The method is well known and widely used for optimizing gas-thermal spraying modes, in particular cold gas-dynamic spraying.

The main input factors, levels, and variance intervals selected for this study are given in Table 1.

The central compositional design was chosen as the basis for the experimental design. This design makes it possible to take into account not only the linear effects of the factors but also their quadratic and interactive effects [20]. Considering five variable factors, including "star" and central points, the total number of experiments was 47.

To assess the statistical significance of the effect of each of the studied factors and their interactions on the objective functions, an analysis of variance (ANOVA) was conducted. That made it possible to test the hypothesis that the factor has an effect on the objective function, based on the decomposition of the total variance of the analysis results.

Based on these data, a second-order regression equation was constructed, describing the dependence of the final particle velocity V_p on the initial parameters in the given value ranges. The generalized form of this equation takes the form

$$Y = \beta_0 + \sum_{i=1}^{n} \beta_i X_i + \sum_{i=1}^{n} \beta_{ii} X_i^2 + \sum_{i<j}^{n} \beta_{ij} X_i X_j + \varepsilon, \quad (1)$$

where X_i – variable factors (Table 1), β – regression coefficients, ε – random error, Y – output variable (particle velocity V_p).

The calculation of the regression coefficients was performed by the least squares method. The adequacy of the model was checked using the Fisher criterion, which assesses the statistical significance of the regression model as a whole, as well as by the coefficient of determination R^2.

The derived regression equation makes it possible to predict the particle velocity at the nozzle exit for various combinations of gas parameters at the nozzle inlet and its geometric parameters. This serves as the basis for further optimization of the spraying process.

Table 1

Input factors, levels and ranges of variance

Factor, designation	Unit of measurement	Level			Variance interval
		–1 (min)	0 (mean)	+1 (max)	
X_1: Critical nozzle diameter, d_{crit}	mm	1	2	3	1…3
X_2: Nozzle outlet diameter, d_{ex}	mm	5	7,5	10	5…10
X_3: Length of the expansion part, l_{conv}	mm	80	115	150	80…150
X_4: Stagnation temperature, T_0	°C	300	500	700	300…700
X_5: Stagnation pressure, P_0	MPa	0.8	1.65	2.5	0.8…2.5

5. Supersonic nozzle design results

5. 1. Structure of the nozzle design approach

The structure of the proposed approach is shown in Fig. 2.

The task of the first stage is to build an experimental plan in order to minimize the number and study the comprehensive influence of the main geometric parameters of the nozzle and the gas parameters at the inlet on the particle velocity. This stage is carried out using the central compositional plan for building a multifactorial experiment.

At the second stage, the gas flow parameters in the nozzle are calculated using the known isentropic gas-dynamic model in accordance with the developed experimental plan. After determining the gas parameters in the nozzle, calculations are performed for the temperature and velocity of the powder particles of the given material and the diameter in this flow.

At the third stage, an analysis of variance (ANOVA) is performed and regression equations for the particle velocity at the nozzle outlet are derived. These equations generalize the dependence on gas stagnation pressure and temperature, the critical and output diameters of the nozzle and the length of the expansion part, allowing us to quantitatively assess their influence on the output velocity of the particles.

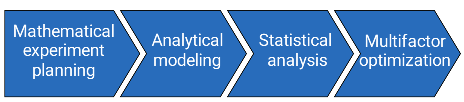

Fig. 2. Structure of the proposed approach to designing nozzles for cold gas dynamic spraying

At the last, fourth stage, multifactorial optimization is performed. The critical particle velocity for effective adhesion to the substrate and the flow pressure value at the nozzle outlet (without overexpansion) were selected as the objective function, taking into account the given value of the gas flow rate through the nozzle.

5. 2. Results of calculating the particle velocity and building the regression equation

According to the developed plan, the calculation of the flow and particle parameters in the nozzle was performed using a one-dimensional isentropic model. Performing the analysis of variance made it possible to establish that the *p*-value for most factors and their interactions is less than 0.05, which is evidence of a statistically significant effect on the result. It was established that the most significant factors affecting the powder particle velocity are the gas stagnation pressure P_0, the stagnation temperature T_0 and the geometric parameters of the nozzle (d_{crit}, d_{ex}, l_{conv}). Similar conclusions were drawn in [21]. On the contrary, some interactions ($d_{crit}-T_0$, $d_{ex}-l_{conv}$, $d_{ex}-T_0$, $l_{conv}-P_0$) were not significant and were excluded from the model without loss of accuracy.

According to the results of the analysis of variance, it was found that the *F*-criterion of the model was 1756.80, which indicates its high confidence.

To check the adequacy of the model, the standard deviation, coefficients of determination (R^2, adjusted R^2, predicted R^2), coefficient of variation (C.V. %) and the coefficient "Adeq Precision", which characterizes the signal/noise ratio, were calculated. The results of this statistical analysis are given in Table 2.

The regression equation in uncoded studied factors for the velocity of aluminum powder particles with a diameter of 25 μm at the nozzle exit takes the form

$$\begin{aligned}V_p &= 70.045-20.14541d_{crit}-4.78361d_{ex}+\\&+1.50013l_{conv}-0.303053T_0+115.1584P_0-\\&-2.7200d_{crit}d_{ex}-0.070893d_{crit}l_{conv}-0.002875d_{crit}T_0-\\&-5.33824d_{crit}P_0+0.019143d_{ex}l_{conv}+\\&+0.000862d_{ex}T_0+1.44412d_{ex}P_0+0.001071l_{conv}T_0-\\&-0.022689l_{conv}P_0+0.080919T_0P_0-0.050109d_{crit}^2-\\&-0.680017d_{ex}^2-0.,004572l_{convc}^2-0.000283T_0^2-\\&-24.77524P_0^2.\end{aligned} \quad (2)$$

Using our model, plots were constructed showing the effect of the studied parameters on the velocity of an aluminum powder particle with a diameter of 25 μm in the specified ranges of values (Fig. 3).

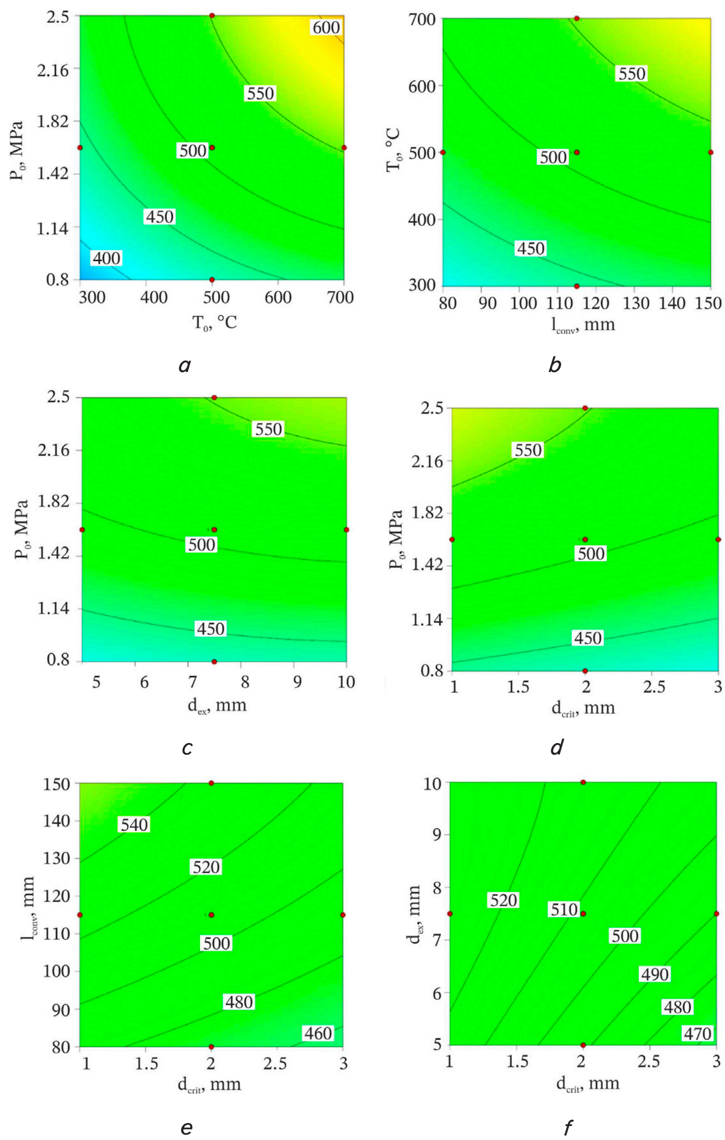

Fig. 3. The influence of the studied factors on the velocity of an aluminum powder particle with a diameter of 25 microns: *a* – T_0, P_0; *b* – l_{conv}, T_0; *c* – d_{ex}, P_0; *d* – d_{crit}, P_0; *e* – d_{crit}, l_{conv}; *f* – d_{crit}, d_{ex}

Table 2

Statistical characteristics of the model and studentized residuals

Indicator	Std. Dev.	Mean	C.V. %	R^2	Adjusted R^2	Predicted R^2	Adeq. Precision
Value	2.96	480.09	0.6163	0.9993	0.9987	0.9972	182.4657

Using the proposed approach, the particle velocities of powders of other materials can be calculated in a similar way and the influence of various process parameters on them can be assessed.

5. 3. Optimization of geometry and gas parameters at the nozzle inlet

The main goal of the optimization stage was to find such a combination of values of the studied parameters that would ensure the achievement of the maximum possible velocity of aluminum particles with a diameter of 25 μm at the nozzle outlet under the condition of a given gas flow rate through the nozzle. The nozzle was designed for the following gas stagnation parameters: pressure $P_0 = 2.5$ MPa and temperature $T_0 = 650$°C.

The gas flow rate for the CGS process, which is implemented at an operating pressure of up to 2.5 MPa, is within 1.0–1.5 m^3/min. The calculation of the mass air flow rate through the nozzle was performed using the following equation from [19]

$$\dot{m} = B\frac{P_0}{\sqrt{T_0}}Sq(\lambda), \tag{3}$$

where P_0 is the gas stagnation pressure; T_0 is the gas stagnation temperature; S is the cross-sectional area for which the calculation is made; $q(\lambda)$ is the gas-dynamic flow function;

B is a constant that depends on the gas properties

$$B = \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}}\sqrt{\frac{\gamma}{R}}.$$

where γ is the adiabatic index; R is the gas constant.

For air, which was used as the working gas in the study, $B = 0.04041$ s·K$^{0.5}$/m.

At $\lambda = 1$, the mass flow rate for the gas corresponding to the supersonic flow regime in the Laval nozzle can be written as

$$\dot{m}_* = B\frac{P_0}{\sqrt{T_0}}S_*. \tag{4}$$

Calculations have shown that to ensure a gas flow rate of 1.0 m^3/min at $P_0 = 2.5$ MPa and $T_0 = 650$°C, the critical nozzle diameter d_{crit} is 2.0 mm.

To ensure sufficient acceleration of the gas flow and powder particles, the following geometric parameters were set for the expanding part of the nozzle: length $L = 130$ mm and outlet diameter $d_{exit} = 5.5$ mm.

To optimize the nozzle geometry, certain conditions were set. First, the pressure of the gas flow at the nozzle outlet should be equal to atmospheric pressure or be slightly higher than 0.1 MPa. This is the key to a stable flow inside the nozzle and an increase in the velocity of particles in the nozzle before they are released into the environment. The second important condition is that the powder particles reach critical velocity values necessary for adhesion to the surface when the gas flow with powder flows onto it. For aluminum powder with a particle size of 25 μm, the critical velocity for the CGS process is 550 m/s. This value was determined based on experimental and theoretical data [22–25].

Fig. 4 shows (in yellow) the operating mode range in which the designed nozzle ensures that aluminum powder particles with a diameter of 25 μm achieve the critical deposition velocity $V_{crit} = 550$ m/s.

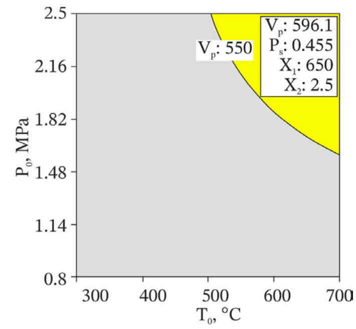

Fig. 4. Range of gas stagnation pressure and temperature values that provide the velocity of an aluminum particle with a diameter of 25 μm for optimized nozzle geometry

Fig. 5 shows the geometry of the internal channel of the optimized nozzle for cold gas-dynamic spraying of aluminum powder with an operating gas pressure of 2.5 MPa.

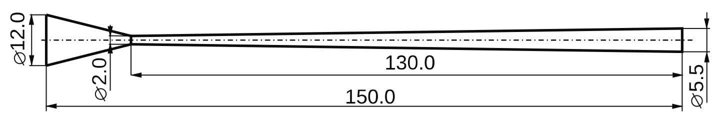

Fig. 5. Optimized nozzle geometry

The resulting nozzle provides the necessary speed for the adhesion of aluminum powder particles with a diameter of 25 microns at a gas stagnation pressure of 2.5 MPa and a stagnation temperature of 650°C. In this case, the gas flow rate through the nozzle is 1.0 m^3/min. The inlet and outlet diameters of the nozzle, as well as its total length, correspond to the values of existing serial installations for CGS with an operating pressure of about 2.5 MPa.

6. Discussion of refults of calculation and optimization of nozzles for cold gas dynamic spraying

We have devised an approach to designing supersonic nozzles for CGS and optimizing spraying modes, which is based on the integration of the isentropic model and methods of statistical experimental design. The proposed approach allowed us to derive a polynomial regression equation that describes the nonlinear nature of the influence of the gas stagnation pressure and the geometric characteristics of the internal nozzle channel on the speed of powder particles under a given gas flow rate. The established quantitative regularities of the speed of aluminum particles from the studied factors create the basis for building algorithms for automated design of supersonic nozzles for CGS without the need to perform numerical gas-dynamic calculations at the stage of preliminary geometry selection.

In this study, the nozzle design approach is implemented using aluminum powder as the starting material due to its wide application in low and medium pressure (up to 2.5 MPa) CGS systems operating on compressed air. Since the CGS technology is often used to restore damaged surfaces of aluminum alloy parts, the use of aluminum in the simulation has direct applied value. The particle diameter of 25 μm was chosen because this value corresponds to the average size of the powders used for CGS.

The approach is not limited to the selected material, fraction size, and can be implemented for other variable parameters of the CGS process and objective functions.

Our results from the analysis of variance (Table 2) showed high adequacy and consistency of the model. In particular, the predicted R^2 (0.9972) and the adjusted R^2 (0.9987) differ by less than 0.2%, which is a sufficiently high indicator and indicates a strong predictive ability of the model. The value of Adeq Precision exceeds the threshold of 4 times, making 182.47, which is a sign of a high signal-to-noise ratio in the model. According to this indicator, it is also concluded that the model can be used to predict the particle velocity or optimize the nozzle geometry and gas parameters at the inlet in the studied value ranges. Such results can be explained by the fact that the obtained regression model makes it possible to take into account not only the influence of individual factors but also their quadratic and pairwise interactions.

From the plots shown in Fig. 3 constructed based on the results of the analysis of variance and the derived equation (2), the patterns of the influence of gas parameters on the particle velocity were established. The gas stagnation temperature has the greatest effect on the acceleration of powder particles, which is explained by the increase in the speed of sound of the gas in the nozzle with an increase in its operating temperature at the inlet. This, in turn, ensures the achievement of a higher speed of the gas flow and, accordingly, of the particles fed into the flow.

Obtaining the calculated particle speed of 596 m/s, which exceeds the critical speed of aluminum powder spraying of 550 m/s [22–25], is explained by the fact that a combination of geometric parameters of the nozzle was found with the set gas parameters. The resulting nozzle and gas parameters give an optimal gas velocity profile along the axis.

The proposed approach to calculating and optimizing nozzles for CGS has a number of advantages compared to similar known ones. Unlike studies by other authors who were engaged in searching for optimal modes for existing nozzles [3], or exclusively the influence of geometry on acceleration [25], the proposed approach combines these tasks into one comprehensive study. Minimizing the number of calculations for a complex and multifactorial CGS process makes it possible to quickly assess the influence of the studied factors in the given ranges of values and proceed to the search for their optimal values. This allows us to assert that the limitations of existing simplified or isolated approaches [26] to designing nozzles for CGS have been overcome. The proposed approach makes it possible to approach the design not only from the standpoint of guaranteed achievement of the critical spraying speed by increasing the gas parameters but also taking into account the cost-effectiveness of the process. Minimizing gas consumption in the spraying process is especially important in the case of using expensive gases, such as helium.

The scope of application of our results includes aircraft and machine-building enterprises engaged in the development of technological processes for spraying protective and restorative coatings. The calculated supersonic nozzle is expedient to be used for mobile and stationary medium-pressure CHN installations (up to 2.5 MPa), operating on compressed air or nitrogen, for applying coatings from aluminum powder with an average particle size of 25 microns.

Potentially expected effects from the implementation of the proposed approach are: reduction of the time for designing nozzles for CGS by minimizing the number of their full-scale tests; reduction of the time for developing operations and selecting optimal spraying modes; increasing the stability of the spraying process due to the coordination of the nozzle geometry and gas parameters at the inlet and ensuring the specified coating quality parameters by guaranteed achievement of critical velocity by particles.

For the correct application of our results in practice, it is necessary to take into account the limitations of this study. They are due to the assumptions adopted in the calculations of the isentropic gas-dynamic model. Friction and heat exchange of the flow with the nozzle walls, as well as the formation of a boundary layer on the inner walls of the nozzle, are what distinguishes the real flow from that adopted in the model. As a result, the actual values of the particle velocity are slightly lower than the calculated ones. Despite this fact, in this study the obtained particle velocity exceeds the critical value and compensates for the assumptions made in the calculations.

Along with the above limitations, the proposed approach has certain disadvantages. First, it is not possible to predict the appearance of local compression jumps inside the nozzle. Second, it ignores the radial non-uniformity of the flow velocity in the nozzle. Accordingly, the velocity of the powder particles in such a flow will be non-uniform. Such shortcomings of the approach overestimate the speed of powder particles at the nozzle exit.

Further research may focus on experimental validation of our results and verification of the approach; expansion of the range of materials; transition to optimization based on the criterion of coating quality, etc.

7. Conclusions

1. The structure of a comprehensive approach to the design of nozzles for CGS has been devised. Its feature is the combination of analytical modeling, statistical planning of the experiment and processing of results, as well as multifactor optimization. Unlike known methods, this makes it possible to minimize the number of necessary calculations and establish quantitative patterns of the influence of gas parameters at the nozzle inlet and its geometry on the velocity of powder particles at the nozzle outlet.

2. Using the isentropic gas-dynamic model, the velocity of aluminum powder particles with a diameter of 25 μm in the channel of a supersonic nozzle for CGS has been calculated. The initial data used were the gas stagnation pressure and temperature, the critical and outlet diameter of the nozzle, and the length of its expansion part. A variance analysis of our results was performed; significant factors and their interaction on the objective function – the velocity of an aluminum powder particle with a diameter of 25 μm at

the nozzle outlet – were determined. A regression equation was constructed that describes the relationship between the velocity of aluminum powder particles with a diameter of 25 μm and the studied variable factors in the given ranges of values. The regularities of the influence of the gas stagnation pressure and temperature, the critical and output diameter of the nozzle, the length of its expansion part in the given ranges of values on the velocity of aluminum powder particles with a diameter of 25 μm were established.

3. The studied factors were optimized; the geometry of the nozzle was established for aluminum powder with a particle diameter of 25 μm for spraying at a gas stagnation pressure of 2.5 MPa and a braking temperature of 650°C. In this case, the particle velocity obtained at the nozzle exit was 596 m/s at a given minimum value of 550 m/s, taking into account the gas flow rate through the nozzle of 1.0 m^3/min.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors declare the use of generative AI in the research and manuscript preparation process. Tasks delegated to generative AI tools under full human supervision: to check grammar, spelling, and punctuation, to check the correctness of the translation of individual phrases and word combinations during the writing of the draft and final editing of the manuscript text.

Generative AI tool used: Grammarly v1.2.212.1789.

The authors bear full responsibility for the final manuscript.

Generative AI tools are not listed as authors and are not responsible for the final results.

Authors' contributions

Oleksandr Shorinov: Supervision, Methodology, Validation, Writing – review & editing; **Nina Savchenko**: Data Curation, Writing – original draft; **Olga Shypul**: Conceptualization, Data curation, Writing – original draft; **Ihor Zorik**: Methodology, Writing – review & editing; **Serhii Nyzhnyk**: Validation, Writing – review & editing.

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