UDC 621.793:621.515
DOI: 10.15587/2706-5448.2025.345022

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DEVELOPMENT OF SPECIAL COLD SPRAY NOZZLE FOR INTERNAL SURFACE COATING DEPOSITION

Increasing the service life of parts by forming protective and restorative coatings through cold spraying (CS) is a tough scientific and technical challenge. The object of the study is the process of accelerating powder particles in a supersonic rotating nozzle for CS. For CS, it is difficult, and sometimes even impossible, to form coatings on internal and hard-to-reach surfaces. In the practice of using the technology, this is considered one of the most problematic places, which limits the capabilities of the technology.

This paper focused on improving the CS process by developing a new supersonic rotating nozzle for coating deposition on internal and hard-to-reach surfaces of parts, establishing the regularities of the trajectory of motion and acceleration of powder particles in it. During the study, classical methods of computational gas dynamics were used, including methods for investigating two-phase flows. Experimental verification of the modeling results was performed by the pneumatic method of determining the Mach number using a Pitot-Prandtl tube. Numerical modeling of CS processes was performed for two designed rotating nozzles – two-channel and three-channel. The values of the maximum velocity of aluminum powder particles with a diameter of 10 μm at an air stagnation pressure of 4.0 MPa and stagnation temperature of 550°C were obtained: 558 m/s for the two-channel nozzle, and 585 m/s for the three-channel one, which is sufficient for adhesion of particles to the substrate. A three-channel nozzle was chosen for manufacturing and experimental testing. The difference between the experimental and calculated values of the Mach number at the nozzle outlet did not exceed 10%. The presence of two additional nozzles, located in the main channel and directed at an angle to the main flow direction, ensures the rotation of the flow with particles from the initial direction at an angle of approximately 75 degrees, which satisfies the requirements for forming CS coatings.

Keywords: *coating, nozzle geometry, powder, optimization, CFD modeling, part recovery.*

Received: 13.09.2025
Received in revised form: 06.11.2025
Accepted: 27.11.2025
Published: 29.12.2025

How to cite

Shorinov, O., Volkov, A., Savchenko, N., Markovych, S., Danko, K., Ipatov, R. (2025). Development of special cold spray nozzle for internal surface coating deposition. Technology Audit and Production Reserves, 6 (1 (86)), 6–11. https://doi.org/10.15587/2706-5448.2025.345022

1. Introduction

Repairing and restoring parts with manufacturing and operational defects is an effective way to extend their service life. The development of new technical solutions for restoration and repair is a pressing global task, determined by three key aspects: increasing the service life and durability of parts, reducing direct and indirect losses due to critical damage, and preserving the metal stock. Unlike well-known methods of coating formation, such as laser deposition [1], electric spark deposition [2], detonation [3], plasma deposition [4] and other spraying methods, which are characterized by melting of the coating material (powder, wire, etc.), the formation of coatings by CS occurs due to the high-velocity impact of powder particles. In this case, the particle is in a solid state, i.e. its temperature is significantly lower than the melting point of the material from which it is obtained.

The particle velocity is the main factor in the transition from surface erosion to the formation of adhesive bonds [5]. Acceleration of the gas flow and particles fed into this flow occurs in supersonic nozzles (Laval nozzle). The temperature and velocity parameters of the powder particle at the moment of impact depend on the gas parameters at the nozzle inlet (stagnation pressure and temperature), as well as the nozzle's channel geometry. The complex of physical and mechanical properties of coatings, the powder utilization factor, and, in general, the possibility of coating formation largely depend on the above-mentioned factors.

The absence of melting processes during deposition prevents oxidation, as well as structural and phase changes, in the coating and substrate materials [6]. The technology has found its greatest application in the aviation and automotive industries for the deposition of protective coatings, in repair production, and has recently been considered one of the methods of additive manufacturing of parts [7]. Powders of pure metals, alloys and powder mixtures are used as powders for deposition. The introduction of new materials and the search for optimal spraying modes require constant improvement of both technological parameters and equipment design [8]. In this context, the nozzle assembly is the most common object of research [9], as it is used to form a flow with particles, accelerate them, and heat them.

The multifaceted nature and complexity of the processes occurring during CS limit the use of experimental research methods, which are labor-intensive and require substantial material resources. Numerical modeling methods allow to study the fast-moving processes occurring in the channel of a supersonic nozzle for spraying, to establish the laws of acceleration and heating of the powder depending on the process parameters, in particular, the temperature and pressure of the gas, the geometry of the nozzle channel, the material and the size of the powder particle fraction, etc.

Currently, numerical modelling methods are widely used for designing and optimizing the parameters of spraying [10]. Experimental verification of the modeling results confirms the high accuracy of the models and the possibility of their use at the design stages [11]. The use of computational modeling in combination with other research methods allows to shorten the process of finding optimal spraying modes with the identification of the most significant factors that will determine the process of spraying coatings [12].

One of the directions of development of CS technology is the formation of coatings on internal and hard-to-reach surfaces of parts. Traditionally, direct supersonic nozzles are used for the CS process. However, there are some studies on the processes of accelerating two-phase flow in multi-channel and rotary nozzles [13]. Previous studies also emphasize the importance of understanding the gas dynamics of the flow in the nozzle [14], the point of introduction of powder into the gas flow, the influence of gas parameters on the quality of coatings, etc. [15]. The implementation of spraying coatings on internal and hard-to-reach surfaces requires finding the optimal geometry of the supersonic rotary nozzle. For this purpose, it is necessary to conduct a study of the gas dynamics of a two-phase flow in such a nozzle and establish the laws of acceleration and heating depending on the gas parameters at the nozzle inlet, the powder material and the size of its particles.

Therefore, *the object of research* is the process of accelerating powder particles in a supersonic rotating nozzle for CS. *The aim of this research* is to enhance the cold spray coating deposition process for internal and hard-to-reach surfaces of parts.

The research tasks are:

1. To develop a supersonic rotary nozzle for CS, which provides deflection of the gas flow with powder particles at an angle from 70° to 90°.
2. To perform numerical simulation of the gas dynamics of a two-phase flow in the rotary nozzle channel, with the establishment of the patterns of the influence of the flow deceleration temperature on the velocity and trajectory of the aluminum powder particle at the nozzle outlet.
3. To manufacture the designed rotary nozzle; to experimentally determine the Mach number of the flow at the nozzle outlet, and compare the obtained results with the numerical simulation data.

2. Materials and Methods

2.1. Development of CAD models of nozzles

It was proposed to develop a special nozzle for applying cold gas dynamic spraying coatings to internal (hard-to-reach) surfaces.

It is essential to understand that the optimal impact angle of the sprayed powder particles in the cold gas dynamic spraying method should be close to 90°. For this purpose, two designs of multi-channel rotary nozzles were developed: a 2-channel (Fig. 1, *a*) and a 3-channel (Fig. 1, *b*) nozzle.

2.2. Gas flow governing equations

Numerical simulation is often beneficial for analyzing the cold gas dynamic spraying process [16, 17].

To describe the behavior of a gas flow, one can use equations describing the laws of conservation of mass, momentum, and energy [18]:

$$\frac{\partial \rho}{\partial t}+\nabla\cdot\left(\rho\cdot u\right)=0, \tag{1}$$

$$\frac{\partial\left(\rho\cdot u\right)}{\partial t}+\nabla\cdot\left(\rho\cdot u\cdot u\right)=-\nabla P+\nabla\cdot\tau_{eff}, \tag{2}$$

$$\frac{\partial\left(\rho h\right)}{\partial t}+\nabla\cdot\left(u\rho h\right)= =\frac{\partial P}{\partial t}+u\cdot\nabla P+\nabla\left(\lambda_{eff}\nabla T-\sum_i h_i J_i+\tau_{eff}\cdot u\right)+\sum_{i=1}^{N}Q^i, \tag{3}$$

where ρ – the density; u – the velocity vector; t – the time, s; P – the gas pressure; $\tau_{eff}=(\mu+\mu_t)(\nabla u+(\nabla u)^T-2/3I(\nabla u))$ – the effective stress tensor (i. e., the sum of the viscous and turbulent stresses); μ – the viscosity; μ_t – the turbulent viscosity; I – the unit tensor; h – the enthalpy of the mixture; $\lambda_{eff}=\lambda+\lambda_t$ – the effective thermal conductivity; λ – the laminar heat conductivity; $\lambda_t=C_p\mu_t Pr_t^{-1}$ – the turbulent heat conductivity; C_p – the specific heat; Pr_t – the turbulent Prandtl number; T – the temperature;

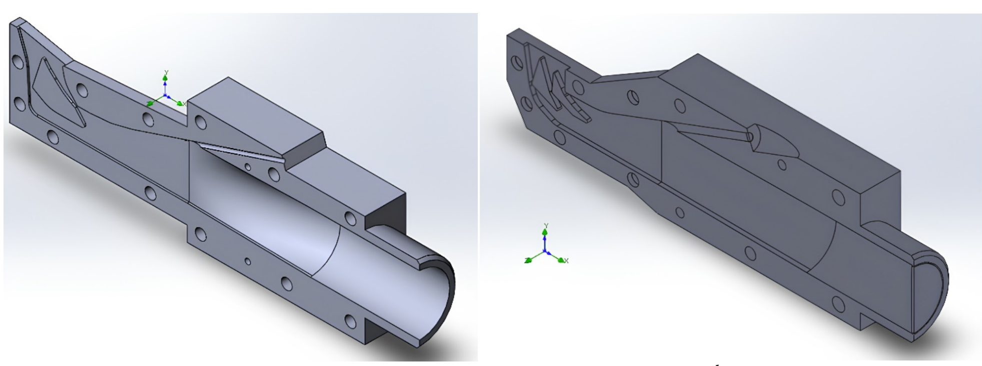
$$h_i=\int_{T_{ref}}^{T} C_{rep,i}\,\mathrm{d}T,$$

where T_{ref} (297 K) – the gas enthalpy i; J_i – the diffusion rate vector of species i; Q^i – the heat.

The SST turbulence model was used to describe the behavior of a wall-bounded flow. According to this model, turbulent viscosity is defined by

$$\mu_T=\frac{0.31\rho k}{\max\left(0.31\omega;\Omega F_2\right)}, \tag{4}$$

where $F_2=tanh(arg_2^2)$; $\arg_2=\max\left(2\frac{\sqrt{k}}{0.09\omega y};\frac{500\nu}{y^2\omega}\right)$; the function is equal to one for the boundary layer and zero for the free layer, respectively; $\Omega=(\partial u/\partial n)$ – the derivative of the flow rate on the normal to the wall; k and ω – the turbulence kinetic energy and the specific dissipation rate, respectively.



a *b*

Fig. 1. CAD models of the developed multi-channel rotated nozzles: *a* – 2-channel; *b* – 3-channel

 ISSN-L 2664-9969; E-ISSN 2706-5448

To determine the turbulent kinetic energy (k) and the specific dissipation rate (ω), subtractions from:

$$\frac{\partial \rho k}{\partial t}+\frac{\partial}{\partial x_i}\left(\rho v_i k\right)=\tau_{ij}\frac{\partial v_i}{\partial x_j}-\beta^{*}\rho\omega k+\frac{\partial}{\partial x_i}\left(\left(\mu+\sigma_k\mu_t\right)\frac{\partial k}{\partial x_i}\right), \quad (5)$$

$$\frac{\partial \rho\omega}{\partial t}+\frac{\partial}{\partial x_i}\left(\rho v_i \omega\right)=\frac{\gamma}{\nu_\tau}\tau_{ij}\frac{\partial v_i}{\partial x_j}-\beta\rho\omega^2+$$
$$+\frac{\partial}{\partial x_i}\left(\left(\mu+\sigma_\omega\mu_t\right)\frac{\partial \omega}{\partial x_i}\right)+2\rho\left(1-F_1\right)\sigma_{\omega 2}\frac{1}{\omega}\frac{\partial k}{\partial x_j}\frac{\partial \omega}{\partial x_j}, \quad (6)$$

where

$$\nu_\tau=\frac{a_1 k}{\max\left(a_1\omega;\partial u/\partial y F_2\right)};$$

the model constant $\Phi_{SST}(\gamma, \sigma_k, \sigma_\omega, \beta, \beta^*)$ is associated with k–ω model constants $\Phi_{k\omega}$ and transformed into the k–ε model $\Phi_{k\varepsilon}$ as $\Phi_{SST}=\Phi_{k\omega}F_1+(1-F_1)\Phi_{k\varepsilon}$; $F_1=tanh(arg_1^4)$;

$$\arg_1=\min\left[\max\left(\frac{\sqrt{k}}{0.09\omega y};\frac{500\nu}{y^2\omega}\right);\frac{4\rho\sigma_{\omega 2}k}{CD_{k\omega}y^2}\right];$$

y – distance to the nearest wall;

$$CD_{k\omega}=\max\left(2\rho\sigma_{\omega 2}\frac{1}{\omega}\frac{\partial k}{\partial x_j}\frac{\partial \omega}{\partial x_j},10^{-20}\right).$$

To simulate the gas dynamic properties of an expanding flow in which thermal energy and pressure energy are converted into kinetic energy as the nozzle area changes, the SolidWorks Flow Simulation software module (Dassault Systèmes SOLIDWORKS Corp.) was used [19].

Using numerical simulation for two-phase gas-solid flow, the air flow field is obtained by solving three-dimensional Navier-Stokes equations using a standard k–ε turbulence model and a non-equilibrium wall function. The second phase, the sprayed powder, is assumed to consist of spherical particles dispersed continuously (gas). In addition to solving the air transport equation, particle trajectories are calculated using the Lagrange method to solve the particle motion equation.

The presence of a border layer on the inner walls of the nozzle significantly affects the Mach number during gas expansion in the nozzle. For this reason, it is necessary to conduct a study using computational fluid dynamics, which considers friction against the inner walls of the nozzle and the thickness of the developing boundary layer in its calculations. The turbulence intensity was 5%, in which the boundary layer was considered turbulent.

2.3. Results validation

To verify the results of the numerical simulation, the method of determining the gas flow velocity using a Pitot-Prandtl tube was selected.

The pneumatic method for determining gas flow velocity is based on Bernoulli's equation. Research into the velocity of supersonic gas flow using total pressure and static pressure values has some distinctive features compared to measurements in subsonic flows. Unlike sonic flow, in supersonic flow a shock wave forms in front of the tube (a direct shock wave) forms in front of the tube. In supersonic flows, the total pressure q_c is measured by the sensor behind the shock wave. Rayleigh's formula is used to determine the Mach number M, which links the total pressure q_c, static pressure P_S, Mach number, and gas adiabatic index k

$$\frac{q_c}{P_s}=\left(\frac{k+1}{2}M^2\right)^{\frac{k}{k-1}}\left(\frac{k+1}{\left(1-k+2kM^2\right)}\right)^{\frac{1}{k-1}}. \quad (7)$$

The Mach number is derived from the formula using the assumption, which works well in practice, that the static pressure before and after the shock wave is the same.

To obtain absolute flow velocity values, it is necessary to know the Mach number and the temperature of the fully decelerated flow. Such measurements are performed using special thermoelectric probes with a deceleration chamber, for which the gas velocity recovery coefficient, depending on the Rayleigh and Knudsen similarity numbers for the flow, is close to one.

3. Results and Discussion

3.1. CFD simulation results

Simulation of gas dynamics in the nozzle was performed at initial temperatures T_0 of 450°C, 500°C, and 550°C and an initial pressure P_0 = 4.0 MPa for Al2024 aluminum powder particles with a particle size of 10 μm.

The simulation was realized in a two-dimensional plane of the nozzle. The calculations were performed with an assumed ambient pressure of 0.1 MPa and a temperature of 20°C.

A detailed analysis of the flow parameters distribution was performed by optimizing the nozzle design and CFD simulation. Fig. 2 and Fig. 3 show the Mach numbers and velocity fields obtained from the simulation at an initial temperature T_0 = 550°C and pressure P_0 = 4.0 MPa.

Also, the trajectories and velocities of 10 μm Al2024 powder particles were obtained (Fig. 4 and Fig. 5) at an initial pressure of 4.0 MPa and a temperature of 550°C, which ensured maximum acceleration of the gas flow in the nozzles under research.

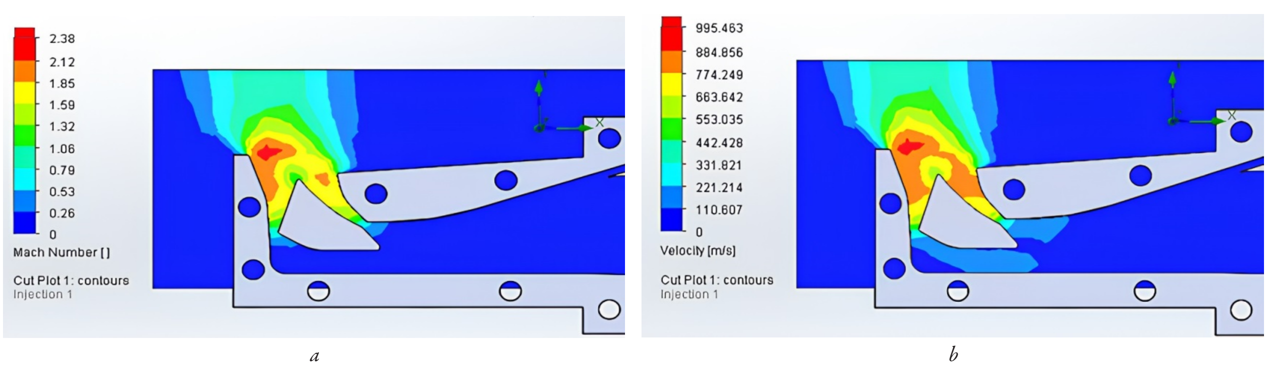
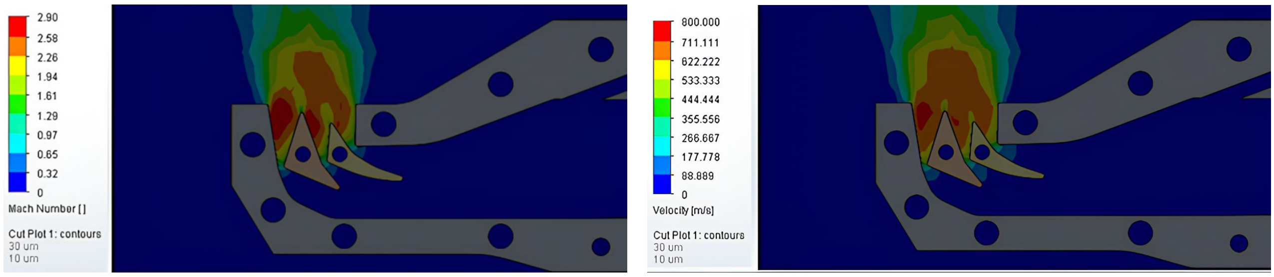
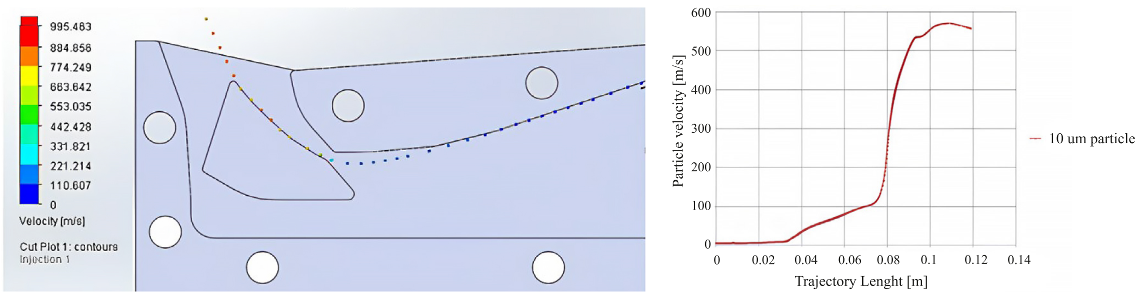


Fig. 2. Simulation results for a 2-channel nozzle at initial temperature T_0 = 550°C and pressure P_0 = 4.0 MPa: *a* – Mach numbers; *b* – velocity fields



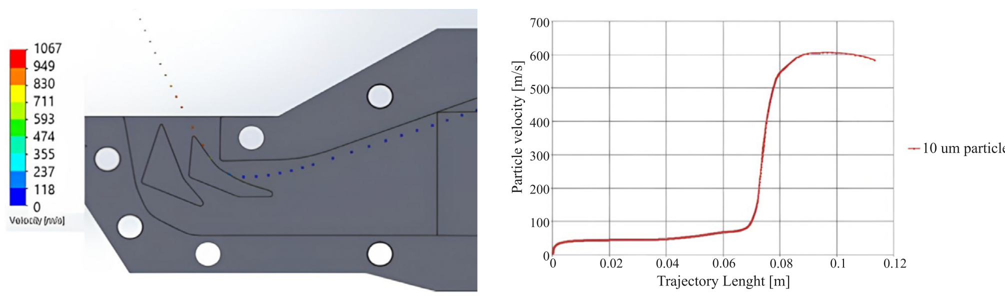
a *b*

Fig. 3. Simulation results for a 3-channel nozzle at initial temperature T_0 = 550°C and pressure P_0 = 4.0 MPa: *a* – Mach numbers; *b* – velocity fields



a *b*

Fig. 4. Trajectory and velocity of 10 μm Al2024 powder particles for a 2-channel nozzle: *a* – particle trajectory; *b* – particle velocity



a *b*

Fig. 5. Trajectory and velocity of 10 μm Al2024 powder particles for a 3-channel nozzle: *a* – particle trajectory; *b* – particle velocity

3.2. Results of the numerical analysis

Based on the above results obtained by simulation, a 3-channel nozzle was manufactured for field testing and further application.

The nozzle is made disassemble (Fig. 6). The two halves, when combined, create the main flow channel, and there are also two inserts to divide the channel into 3 parts. All components were manufactured by milling on a 5-axis CNC machine from steel 12X18H10T.

The manufactured nozzle sample was used to validate the numerical simulation results. For this purpose, the values of total pressure and static pressure, as well as the temperature of the flow at the nozzle outlet, were measured. The nozzle was tested without powder supply to determine the Mach number of the gas flow at the nozzle outlet at a total pressure of 4.0 MPa and flow heating temperatures of 450°C, 500°C, and 550°C.

The laboratory stands for measuring the total pressure and static pressure values using a Pitot-Prandtl tube and the flow temperature is shown in Fig. 7.

According to the obtained values of total pressure q_c and static pressure *Ps*, the Mach number was determined for various initial values of gas deceleration temperature at the nozzle inlet. The results are presented in Fig. 8. After testing the blowing powder through the nozzle, it was disassembled to analyze the internal surfaces of the channel. Fig. 9 shows a photograph of the internal surface of the 3-channel rotary nozzle after conducting experimental research.

a *b* *c*

Fig. 6. Manufactured 3-channel rotary nozzle: *a* – general view; *b* – internal geometry; *c* – rotary inserts

Fig. 7. Laboratory stand for measuring total head and static pressure using a Pitot-Prandtl tube

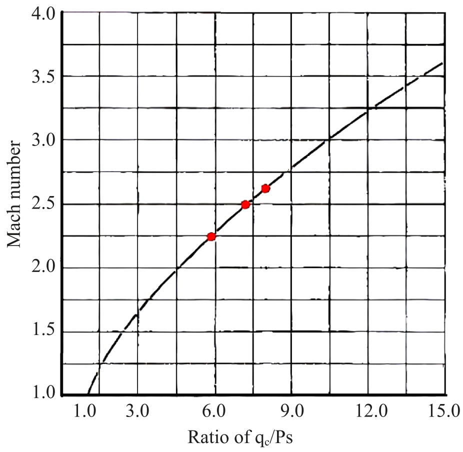


Fig. 8. Results of experimental determination of Mach number based on total pressure and static pressure indicators

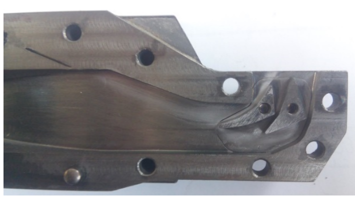


Fig. 9. Trace of particle movement in a gas flow in a 3-channel rotary nozzle

Both variants of the designed nozzle enable not only heating and accelerating particles to critical energy parameters, but also directing the flow of sprayed particles onto hard-to-reach surfaces at an angle of 75–80 degrees (Fig. 4 and Fig. 5).

According to the results of numerical simulation, the velocity of aluminum powder particles with a diameter of 10 μm at the nozzle outlet at air stagnation temperatures of 450°C, 500°C and 550°C and a constant stagnation pressure of 4.0 MPa was obtained.

With increasing stagnation temperature, an increase in the velocity of powder particles was observed. The particle velocity increases due to an increase in the gas velocity, as the local gas temperature in the nozzle also increases with an increase in the stagnation temperature at the nozzle inlet. As a result, the local speed of sound also increases. The gas velocity is the multiplication of the speed of sound velocity and the Mach number, which is related to the channel geometry and can be calculated from the known cross-sectional area of the nozzle. Powder particles fed into the gas flow are accelerated due to the aerodynamic drag force, which increases with the increase in gas velocity.

Accordingly, the maximum velocity of aluminum powder particles with a diameter of 10 μm was obtained for both nozzles under CFD-analysis at a maximum stagnation temperature of 550°C. The three-channel rotary nozzle had higher values of the powder particle velocity at the nozzle outlet – 585 m/s versus 558 m/s for the two-channel one. At the same time, both developed nozzles ensure that the powder particles achieve the critical velocity for spraying aluminum powder with a particle size of 10 μm, which, according to literature data, is from 520 m/s to 660 m/s [20]. The angle of deviation of the flow with powder particles of 10 μm diameter for both nozzles (Fig. 4, *a*, and Fig. 5, *a*) lies within the specified range (70–90 degrees) and corresponds to the recommended values for CS coating deposition. It was found that the deflection angle for the three-channel nozzle (about 75 degrees) is more desirable, since deposition at an angle approaching 90° provides better coating deposition efficiency [21].

Fig. 8 shows the Mach number values obtained experimentally using a Pitot-Prandtl tube at the outlet of the manufactured three-channel rotary nozzle. It can be seen from the figure that the Mach numbers range from 2.25 to 2.6 for gas stagnation temperatures of 450°C, 500°C and 550°C (marked by red dots) and a stagnation pressure of 4.0 MPa. The error in determining the Mach number by the pneumatic method in the nozzle for CS is within ± 5% and is associated with losses of total gas pressure in the nozzle [22]. Comparison of the results of numerical modeling (Fig. 3, *a*) and experimental determination of the Mach number (Fig. 8) showed that the discrepancy in the values does not exceed ± 10%.

At the final stage, experimental studies were carried out with the introduction of aluminum powder with an average particle diameter of 10 μm into the flow. After a series of experiments, the nozzle was disassembled and its internal surfaces analysed for their state. A trace of the flow with particles in the nozzle channels was detected. Comparison of the particle tracks obtained by numerical modeling (Fig. 5, *a*) and experimentally (Fig. 9) allowed to conclude that the results obtained by modeling are correct, and the correctness of the selected injection location and the angle of inclination of the powder-transporting channel.

A feature of the obtained results is in scientific substantiation of the poss bility of using the proposed rotary nozzle to improve the CS process for coating deposition on internal and hard-to-reach surfaces of parts, as well as establishing the regularities of the trajectory of motion and velocity of powder particles in the nozzle depending on the number of channels used in it to deviate the two-phase flow from the direction of the main flow.

The limitations of the proposed research include a narrow range of operating temperatures and pressures, as well as the analysis of a single powder material and its particle size. To eliminate these limitations, it is recommended to conduct further comprehensive studies to establish the features of the gas dynamics of the two-phase flow in the proposed rotary nozzle from the gas parameters (stagnation pressure and temperature) at the nozzle inlet in a wide range of values, as well as different powder materials and particle sizes.

4. Conclusions

1. To expand the capabilities of CS technology for coatings deposition on internal and hard-to-reach surfaces of parts, two variants of the supersonic rotary nozzle were designed: two-channel and three-channel.
2. The presence of additional rotary channels in the outlet part of the nozzle provides deflection of the gas flow with particles from the direction of the main flow at an angle of 70–75 degrees, which is recommended for CS. According to the results of numerical modeling, the velocity of aluminum powder particles with a diameter of 10 μm at the exit of the designed rotary nozzles, as well as the trajectory of powder particles in the nozzle and at the exit from it were obtained. It was found that the three-channel nozzle yields higher particle velocities at the nozzle outlet compared to the two-channel nozzle (585 m/s versus 558 m/s, respectively).
3. The process of acceleration of gas and aluminum powder particles in a three-channel nozzle was manufactured and experimentally investigated. Comparison of the results of experimental studies of the Mach number at the nozzle outlet by the pneumatic method using a Pitot-Prandtl tube and numerical modeling showed a discrepancy of values within ± 5%.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

Financing

The research was performed without financial support.

Data availability

The manuscript does not have associated data.

Use of artificial intelligence

When preparing the manuscript, an AI assistant was used to check grammar, spelling, and punctuation (Grammarly v1.2.212.1789). All changes suggested by the AI assistant were made under the full author's control. The specified tool was also used to verify the correctness of the translation of individual phrases and word combinations during both the draft and final editing stages, without altering the author's style, adding or generating any parts and/or the entire text. Adjustments to the brightness, contrast, color balance, and sharpness of the original author's images (Fig. 2–5) were made using an online image editor (https://www.iloveimg.com/ua/upscale-image) under the authors' supervision.

Authors' contributions

Andrii Volkov: Conceptualization, Data curation, Writing – original draft; ***Oleksandr Shorinov***: Supervision, Methodology, Validation, Writing – review and editing; ***Serhii Markovych***: Conceptualization, Validation; ***Kostiantyn Danko***: Methodology, Writing – review and editing; ***Nina Savchenko***: Data curation, Writing – original draft; ***Roman Ipatov***: Validation, Writing – review and editing.

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