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Analysis of the influence of the geometry of the working zone on the distribution of the electric field in powder coating systems

Abstract. The aim of the study was to establish the features of the spatial formation of the electric field in electrostatic powder coating systems and its influence on the powder deposition indicators and coating uniformity. The methodology combined a bench-top comparative experiment, three-dimensional electrostatic modelling of the "corona electrode – charged torch – grounded product" system, non-destructive measurement of the dry film thickness, determination of the powder deposition efficiency and statistical analysis of electrostatic and technological indicators for four configurations of the working zone. It was established that the cylindrical configuration was characterised by the smallest spatial heterogeneity of the electric field: the coefficient of variation of the electric field strength was 0.178 versus 0.261 for the rectangular, 0.311 for the combined and 0.330 for the configuration with a variable interelectrode distance. For this configuration, the highest value of powder deposition efficiency was also recorded – 74.9%, the largest average coating thickness was 77.5 μm and the smallest value of the coefficient of variation of the coating thickness was 0.093. For the combined configuration and the configuration with a variable interelectrode distance, the powder deposition efficiency decreased to 63.1% and 60.7%, and the coefficient of variation of the coating thickness increased to 0.201 and 0.229, respectively, which reflected the transition of electrostatic heterogeneity into technological non-uniformity of the coating. Statistical analysis confirmed the significance of inter-configuration differences for the coefficient of variation of the electric field strength and the coefficient of variation of the coating thickness. Integral correlation analysis showed a close positive relationship between the coefficient of variation of the electric field strength and the coefficient of variation of the coating thickness ($r = 0.84$; $p = 0.001$), and local correlation analysis between the electric field strength and the coating thickness showed a statistically significant positive relationship ($r = 0.79$; $p < 0.001$). The practical significance of the results lies in the possibility of the use in the design, setup, and optimisation of working zones in electrostatic powder coating systems to improve the efficiency of powder deposition and coating uniformity

Keywords: electrostatic spraying; deposition efficiency; spatial heterogeneity; interelectrode distance; dry film thickness; coefficient of variation

INTRODUCTION

Electrostatic powder coating belongs to the technologies for forming protective and decorative coatings, in which the final result is determined not only by the process parameters, but also by the spatial conditions of powder deposition.

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The geometry of the working zone sets the configuration of the electric field, changes the trajectories of charged particles and affects the local intensity of the deposition on the surface of the part. As a result, the spatial features of the working volume can cause uneven layer thickness, the appearance of defective areas and a decrease in coating reproducibility even under the same technological conditions. Under such conditions, research attention shifts from general regime parameters to the spatial organisation of spraying and geometrically determined electrostatic factors. In the work of N. Ayrilmis (2022), electrostatic powder coating is considered as a technological system within which the result of the process is determined by the coordination of spraying parameters, substrate properties and powder deposition conditions. It is shown that the uniformity of the coating depends on the organisation of the application process no less than on the characteristics of the material, which deduces the spatial conditions of layer formation into a separate analytical plane. This approach is consistent with the work of J.M. Gimenez (2024), in which multiscale modelling of electrostatic powder spraying was used to describe the transport of particles and the formation of the deposited layer under the action of electrostatic forces. The results obtained showed that numerical modelling makes it possible to identify the influence of the configuration of the application zone and local conditions of particle motion on the nature of the distribution of the coating on the surface.

Consideration of the spatial variability of the layer thickness in automated spraying systems is presented in the work of C. Wang *et al*. (2025), where the uniformity of deposition was investigated based on a theoretical description, numerical modelling and experimental verification. The authors established that the spraying distance, movement speed and parameters of the processing zone directly affect the layer thickness and the degree of its spatial variability. In the article by Y. Tsapko *et al*. (2023), the authors examined the regularities of the formation of a polymer shell by powder paint under controlled technological process conditions. It was found that the characteristics of the formed layer changed depending on the application and heat treatment parameters. A similar relationship between the process conditions and the properties of the coating was also traced in the publication by O. Chyhyrynets *et al.* (2025), devoted to the optimisation of the system composition to increase the corrosion resistance of paint and varnish coatings. In this study, the functional properties of the layer are associated with the controlled parameters of the technological process, and not only with the characteristics of the initial components. In a similar aspect, V.I. Gots *et al*. (2023) considered powder coating as a technologically controlled system in which the final result depended on the conditions of layer formation and the consistency of the process parameters. The authors found that changing the technological parameters affected the operational properties of the coating, which indicated the dependence of its final characteristics on the formation mode. A similar approach is presented in the work of V. Korzhyk *et al*. (2025), where the structural features of multilayer epoxy composite coatings on a metal-ceramic basis were investigated. Within the framework of the analysis, a connection between the operational characteristics of the coating and the method of its formation was established, which indicated the dependence of the final result on the parameters of the technological environment.

Further development of this approach is presented in the study by V. Subbotina *et al*. (2020), where the influence of process conditions on the growth kinetics and phase-structural state of coatings on an aluminium alloy was analysed. It was found that changing the parameters of the working environment changed the mechanism of layer formation and its final characteristics. The applied value of the stability of powder coating parameters was highlighted in the work of A. Baxevani *et al*. (2025), where the influence of powder coating and preliminary anodising on the corrosion resistance of an aluminium alloy was considered. The authors showed that the quality of the formed layer determines not only the state of the surface, but also the nature of its functioning under operational conditions. A separate aspect of this issue was reflected in the work of A. Kasdi *et al*. (2023), where, based on experimental and numerical modelling of corona discharge in the "wire-cylinder-plane" system, it was established that changing the geometry of the electrode configuration changes the characteristics of the electrostatic field, spatial distribution of voltage, and charging efficiency. This provided grounds for considering the configuration of the working zone as a factor associated with the inhomogeneity of the electrostatic action and local features of particle deposition.

Thus, the available publications cover the issues of electrostatic spraying, numerical modelling of particle transport, layer formation conditions and functional properties of powder coatings. At the same time, the influence of the geometry of the working zone on the spatial distribution of the electric field with the subsequent transition to the indicators of powder deposition and uniformity of the formed coating is not fully covered. It also remains insufficiently determined to what extent a change in the shape of the working volume, the presence of local shielding elements and variations in the interelectrode distance change the inhomogeneity of the field and cause local deviations in the thickness of the coating.

In this regard, the purpose of the article was to analyse the influence of the geometry of the working zone on the distribution of the electric field in powder coating systems and to establish a relationship between the field parameters, the efficiency of powder deposition and the uniformity of the coating. To achieve this goal, the following tasks were defined: to establish the features of the electric field distribution for different geometric configurations of the working zone, to determine the impact of these changes on the efficiency of powder deposition and coating uniformity, and to compare the results of electrostatic modelling with experimental indicators of coating quality to justify the appropriate configuration of the working zone.

MATERIALS AND METHODS

The study was carried out during November 2025 – January 2026 on the basis of an experimental laboratory stand of electrostatic powder coating with thermal polymerisation. The study was conducted on the territory of a private enterprise in Kyiv, where painting work was performed. The study was conducted in the format of a bench comparative experiment, within which the physical application of powder coating was combined with three-dimensional electrostatic modelling. The geometry of the working zone within the work was defined as a set of spatial parameters of the working volume, the configuration of internal elements and the mutual location of the sprayer and the product. For comparative analysis, four basic configurations of the working zone were selected: a rectangular area measuring 600×600×900 mm, a cylindrical area with a diameter of 700 mm and a height of 900 mm, a combined configuration with local shielding elements, as well as a configuration with a variable geometry of the interelectrode space, within which the distance between the sprayer and the part varied from 180 to 260 mm. The configuration with a variable geometry was used as a model of a spatially inhomogeneous interelectrode space. This approach made it possible to compare the influence of the shape of the working volume, the presence of internal shielding elements and changes in the interelectrode interval on the nature of the electric field distribution and the conditions for the deposition of the powder material. To ensure a unified basis for the experiment, standard steel panels were used, the preparation of which was carried out in accordance with the requirements of ISO 1514:2024 (2024), which regulated the types of test panels and the procedures for the preparation before coating.

The materials of the study were thermosetting polyester powder paint Interpon 610 (AkzoNobel Powder Coatings, Netherlands), intended for protective and decorative coating of metal products for internal use, steel panels measuring 150×100×1 mm, interchangeable geometric inserts for forming different configurations of the working zone and grounded metal sample holders. The recommended polymerisation mode of 180°C for 15 min was adopted for the powder paint. The colour of the material was determined according to the RAL 7035 scale, which reduced the visual error when controlling the uniformity of the coating. The granulometric composition of the powder was controlled by laser diffraction according to ISO 8130-13:2019 (2019) on a Mastersizer 3000+ analyser (Malvern Panalytical, UK/Netherlands). The representative parameter of the particle size distribution was $d_{50} = 34.8$ μm. Only samples with the same substrate material, the same surface preparation scheme and stable electrical contact with ground were included in the sample. Surface preparation included abrasive matting, degreasing with isopropyl alcohol and drying. After completion of the preparatory operations, the average surface roughness was determined by a contact profilometer according to the Ra parameter. The obtained value was 1.3 ± 0.2 μm. Panels with deformations, traces of corrosion, residues of the previous coating, unstable fastening or deviation of geometric dimensions of more than 1% were excluded from the sample. The sample was formed as a target, non-random, consisting of 48 samples: 12 panels for each geometric configuration, with three independent repetitions and four samples in each series.

Experimental powder coating application was performed on a laboratory stand, which included a PEM-X1 electrostatic corona hand sprayer (WAGNER Group, Germany), a Sprint 2 Expert powder feed system (WAGNER Group, Germany), a coating chamber with interchangeable geometric modules, and a local ventilation exhaust unit. The sprayer provided the formation of a charged powder torch, the powder feed system provided the dosed transportation of powder paint to the sprayer, the coating chamber provided the reproduction of various configurations of the working zone, and the local ventilation exhaust unit removed excess powder phase from the spraying chamber. Polymerisation of the coatings was carried out in a BINDER FD 115 drying and polymerisation cabinet (BINDER GmbH, Germany). The main experimental indicator of the consequences of a geometrically determined change in the electrostatic field was the thickness of the dry film and its spatial distribution over the sample surface. The dry film thickness was determined using a digital thickness gauge Elcometer 456 Separate (Elcometer Limited, UK). Coating gloss and adhesion were considered as auxiliary characteristics of the formed layer, since these characteristics were used for accompanying quality control of the coating and were not the main indicators of geometrically determined redistribution of the powder material. Gloss was assessed using a Novo-Gloss 60° glossmeter (Rhopoint Instruments Ltd., UK), and adhesion was determined by the grid cut method using a 107 Cross Hatch Cutter adhesion meter (Elcometer Limited, UK). Three-dimensional modelling of the electrostatic field distribution in the working zone was performed in the Maxwell 2024 R2 software environment (ANSYS, USA).

The research procedure included four consecutive stages. At the first stage, the powder material was standardised and the stability of its particle size distribution was monitored. At the second stage, for each configuration of the working zone, powder coating was applied under the same operating parameters: the voltage on the electrode was 80 kV, the current strength was up to 80 μA, the powder flow rate was 110 g/min, the transport air pressure was 0.6 bar, the spraying distance within the basic series was 220 mm, the temperature in the laboratory was 22 ± 2°C, the relative humidity was 45 ± 5%, the polymerisation temperature was 180°C, and the holding time was 15 min after reaching the metal temperature. At the third stage, a three-dimensional model of the working zone was built in ANSYS Maxwell 2024 R2 and the electric potential distribution φ was calculated. The simulation was performed in a stationary setting for the system "corona electrode – charged torch – grounded product", in which the sprayer potential was set according to the experimental mode, and the surface of the test product was considered as a grounded conductive boundary. The boundary conditions were determined taking into account the geometry of the spraying chamber, the location of the internal elements and the interelectrode distance. The control volume for assessing the field inhomogeneity was formed within the space between the sprayer and the sample surface, i.e., in the zone that directly determined the conditions for the transfer and deposition of charged particles.

The electric field strength was determined as formula (1):

$$E = -\nabla\varphi, \quad (1)$$

where E – the electric field strength vector; φ – the electric potential; ∇ – gradient operator.

The spatial non-uniformity of the field was estimated by the coefficient of variation (formula (2)):

$$CV_e = \sigma_e/\bar{E}, \quad (2)$$

where σ_e – the standard deviation of the electric field strength in the control volume; $\bar{E}$ – the average value of the electric field strength.

The uniformity of the formed coating was determined by the ratio (formula (3)):

$$CV_h = \sigma_h/\bar{h} \quad (3)$$

where σ_h – the standard deviation of the coating thickness; $\bar{h}$ – the average layer thickness.

The powder deposition efficiency η was determined according to the provisions of ISO 8130-10:2021 (2021) as the ratio of the mass of powder material deposited on the surface of the test article to the mass of powder fed into the system during the controlled application interval (formula (4)):

$$\eta = (m_o/m_p) \times 100\%, \quad (4)$$

where m_o – the mass of powder deposited on the sample; m_p – the mass of powder fed to the sprayer during the spraying series.

In the fourth stage, the results of electrostatic modelling were compared primarily with the coating thickness and the coefficient of variation of its spatial distribution to determine whether a geometrically determined change in the electric field distribution caused differences in the conditions of powder deposition and the uniformity of the formed layer. Gloss and adhesion were additionally determined as accompanying coating characteristics, which made it possible to assess whether a change in the spatial uniformity of the layer was accompanied by differences in the external and functional characteristics of the coating. Non-destructive measurement of dry coating thickness was performed in accordance with ISO 2360:2017 (2017) and ISO 2808:2019 (2019), adhesion was determined according to ISO 2409:2020 (2020), and gloss was determined according to ISO 2813:2014 (2014). Within each sample, the coating thickness was measured at nine control points distributed between the central, edge and geometrically shaded areas. Statistical processing of the experimental data was carried out in Microsoft Excel 365 and IBM SPSS Statistics 26. The mean, standard deviation, coefficient of variation and 95% confidence interval were calculated for each series. The normality of the distribution was checked using the Shapiro-Wilk test. To compare two configurations, the Student's t-test for independent samples was used, and to compare three or more configurations, the one-way ANOVA analysis of variance at a statistical significance level of $p < 0.05$ was used. Pearson's correlation analysis was used to assess the relationship between the local electric field strength values at the model control points and the corresponding coating thickness values measured in spatially correlated areas of the sample surface. Error control was ensured by repeated measurements and preliminary calibration of the instruments before each series of experiments. Given the high-voltage nature of the electrostatic process, all operations were carried out under the conditions of mandatory grounding of the equipment, control of electrostatic hazards and compliance with the requirements of IEC TS 60079-32-1:2013 + AMD1:2017 CSV (2017). This approach ensured the reproducibility of experimental conditions and the correctness of comparison of results within the studied working zone configurations.

RESULTS

The influence of the geometry of the working zone on the spatial distribution of the electric field

A comparative analysis of the parameters of the spatial distribution of the electric field in the studied configurations of the working zone showed that the change in the geometry of the interelectrode space was accompanied by differences in the average value of the electric field strength, the degree of spatial dispersion of the field and the value of the coefficient of variation of the electric field strength (CV_e). The identified discrepancies concerned not only the integral level of the electrostatic action, but also the ratio between the areas of local field concentration and the zones of its weakening. With this approach, the coefficient of variation of the electric field strength (CV_e) characterised not the absolute level of intensity, but the measure of the spatial alignment of the field within the control volume. The generalised parameters of the electric field distribution in different configurations of the working zone are given in Table 1.

As shown in Table 1, the geometry of the working zone affected the spatial uniformity of the electric field, and the change in configuration was accompanied by a change in the coefficient of variation CV_e, the nature of local intensity maxima, and the severity of the shielded areas. The smallest value of CV_e was established for the cylindrical configuration, where it was 0.178. This corresponded to the smallest spatial variability of the field within the control volume among the studied variants. In the rectangular configuration, the spatial dispersion of the intensity was higher, and CV_e was equal to 0.261, which reflected a greater dependence of the field structure on the edge and corner segments of the working space. For the combined configuration and the configuration with a variable interelectrode distance, the values of CV_e were recorded as 0.311 and 0.330, respectively, which corresponded to a more pronounced spatial heterogeneity of the electrostatic action.

Table 1. Comparative parameters of electric field distribution for different configurations of the working zone

Work area configuration	$\bar{E}$, kV/m	σ_e, kV/m	CV_e	Local areas of the electric field strength concentration	Shielded/attenuated areas
Rectangular	21.8	5.7	0.261	Moderately pronounced near the central axis of the flare and near the edge transitions	Present in angular and peripheral segments
Cylindrical	23.1	4.1	0.178	Moderate, without sharply localised maxima	Minimally expressed, mainly on the periphery
Combined with local shielding elements	24.4	7.6	0.311	Expressed near shielding elements and in the periaxial zone	Clearly expressed by shielding elements
Variable-distance	20.6	6.8	0.330	Local maxima in areas of reduced interelectrode distance	Expressed in areas of increased interelectrode gap

Source: compiled by the authors

Quantitative differences showed that the average electric field strength did not coincide with the degree of its spatial uniformity. For the combined configuration, a higher average electric field strength was recorded with a simultaneously increased CV_e value. This indicated that the increase in the average strength was not accompanied by a corresponding spatial alignment of the field within the entire working volume. The increase in the local concentration of field lines near the internal elements was combined with the formation of adjacent areas of weakened field, as a result of which the spatial distribution of the strength became more contrasting. Thus, when comparing geometric configurations, not only the integral level of strength was important, but also the degree of its spatial alignment. The nature of the potential redistribution, areas of concentration of field lines and shielding areas is shown in Figure 1.

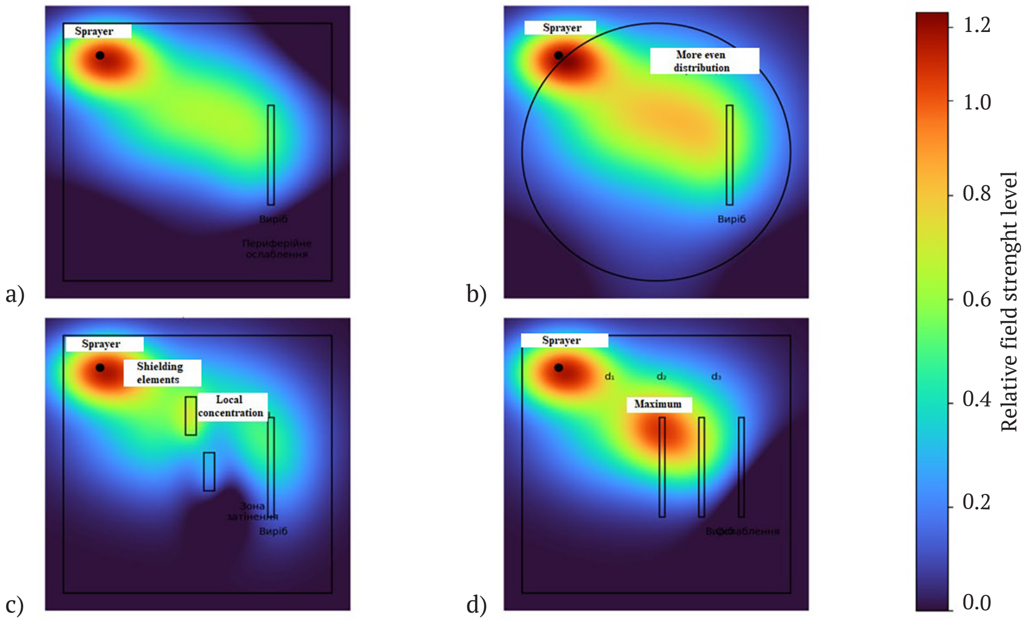

Figure 1. Spatial distribution of electric potential and electric field strength in the studied working zone configurations
Note: a – rectangular configuration; b – cylindrical configuration; c – combined configuration with local shielding elements; d – configuration with variable interelectrode distance. The colour scale reflects the relative level of electric field strength: warm tones correspond to higher values, cold tones to lower ones
Source: compiled by the authors

As shown in Figure 1, changing the geometry of the working zone changed not only the average level of electric field strength, but also its spatial structure, in particular the configuration of local maxima, shaded zones and peripheral areas of attenuation. In the rectangular configuration, the field distribution in the central part of the working volume remained relatively ordered, while in the edge segments and near the corner transitions a decrease in the density of field lines was recorded. Such a distribution reflected the axial organisation of the electrostatic action with peripheral attenuation, which increased with increasing distance from the central trajectory of the torch. This variant was characterised by a gradual change in the spatial uniformity of the field from the centre to the boundaries of the working space. In the cylindrical configuration, the redistribution of potential had a smoother character. The curvilinear boundary of the working space reduced the influence of sharp geometric transitions, as a result of which the lines of force were distributed more evenly, and the peripheral attenuation was less pronounced than in the rectangular variant. This field structure corresponded to the lowest value of CV_e given in Table 1. This configuration was not characterised by the formation of sharply localised maxima or extended shaded zones capable of changing the general structure of the field. This corresponded to the lowest spatial variability of the electrostatic action among the studied variants. The combined configuration with local shielding elements and the configuration with a variable interelectrode distance were characterised by increased spatial heterogeneity of the electric field, but the mechanisms of its formation were different. In the first case, the contrast distribution arose under the influence of internal obstacles: local densification of the lines of force was observed near the shielding elements, while in the shaded segments behind the shielding elements, the intensity decreased. This caused a combination of a high average value of $\bar{E}$ and an increased coefficient of variation CV_e, i.e., an increase in the spatial contrast of the field without a decrease in the general level of electrostatic action. In the second case, the heterogeneity was formed due to the variation of the interelectrode distance: in the zones of the atomiser approaching the surface of the product, local maxima of intensity appeared, while in the areas of the increased gap, the field weakened and dissipated. It was for this configuration that the highest CV_e value was recorded among all the studied options. A comparison of the configurations showed that a higher average level of intensity did not necessarily correspond to a greater spatial uniformity of the field, while CV_e reflected the degree of its spatial stability. The lowest CV_e value was recorded for the cylindrical configuration, while the combined and variable-distance configurations were characterised by a more contrasting distribution with a combination of zones of concentration and field weakening. Therefore, the geometry of the working zone determined not only the shape of the lines of force, but also the nature of the spatial redistribution of the electrostatic action, which formed the basis for analysing the efficiency of powder deposition and coating formation.

The influence of the working zone configuration on the efficiency of powder deposition and coating uniformity

The technological manifestation of the established electrostatic differences was traced in the indicators of the efficiency of powder deposition and the spatial distribution of the coating thickness. A comparison of η, $\bar{h}$, σ_h, CV_h and local thickness values in the control zones showed that changing the configuration of the working zone affected not only the integral level of powder material deposition, but also the nature of local layer growth in the central, edge and geometrically shaded segments of the surface. The differences were most noticeable between the configurations with a lower degree of spatial heterogeneity of the electric field and the variants in which the intensity distribution had a more contrasting nature. The distribution of the coating thickness at the control points is shown in Figure 2.

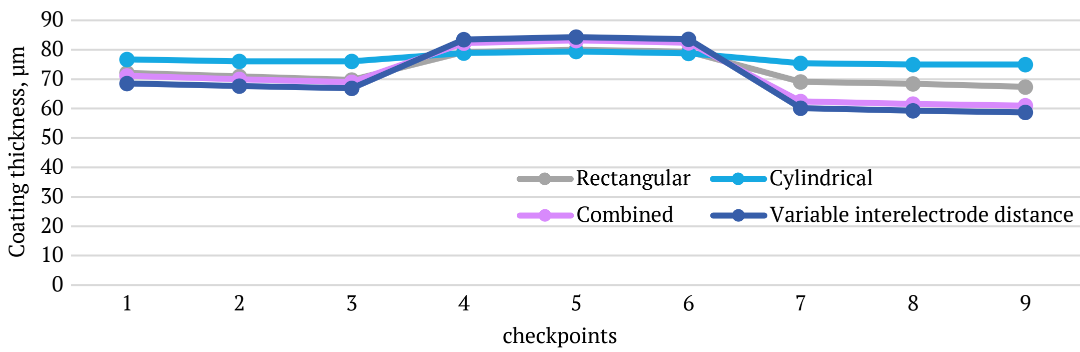

Figure 2. Distribution of coating thickness at control points for different working zone configurations

Source: compiled by the authors based on ISO 2360:2017 (2017), IEC TS 60079-32-1:2013+AMD1:2017 CSV (2017), ISO 2808:2019 (2019)

As shown in Figure 2, the nature of the spatial distribution of the coating thickness depended on the working zone configuration. The smallest zonal contrast was recorded for the cylindrical configuration: the difference between the central and geometrically shaded zones was 3.9 µm. This corresponded to the lower spatial variability of the deposition within the product surface. The rectangular configuration occupied an intermediate position: in the central part of the surface the thickness remained relatively stable, and in the direction of the edge and shaded segments it decreased gradually, without a sharp local decline. The combined configuration with local shielding elements was characterised by a pronounced zonal contrast: the coating thickness varied from 82.7 µm in the central zone to 61.8 µm in geometrically shaded areas, which reflected the influence of shielding effects on the spatial distribution of the deposited material. In the configuration with a variable interelectrode distance, the difference between the central and geometrically shaded zones reached 24.8 μm. In this variant, the central areas were characterised by increased layer growth, while the largest thickness decrease was recorded in the remote segments. Therefore, in the combined configuration and in the configuration with a variable interelectrode distance, the greatest contrast was observed between the zones of increased and decreased deposition, while the cylindrical configuration was characterised by a more uniform distribution of the coating. To summarise the technological consequences of changing the geometry of the working zone, the integral indicators of powder deposition efficiency and coating uniformity are given in Table 2.

Table 2. Powder deposition efficiency and coating uniformity indicators for different working zone configurations

Work area configuration	%	$\bar{h}$, μm	σ_h, μm	CV_h	Central zone, microns	Edge zone, μm	Geometrically shaded area, μm
Rectangular	68.4	74.8	10.9	0.146	79.6	71.2	68.7
Cylindrical	74.9	77.5	7.2	0.093	79.1	76.4	75.2
Combined with local shielding elements	63.1	73.6	14.8	0.201	82.7	70.4	61.8
Variable-distance	60.7	71.9	16.5	0.229	84.1	68.1	59.3

Source: compiled by the authors based on ISO 2360:2017 (2017), ISO 2808:2019 (2019), ISO 8130-10:2021 (2021)

In conformity with the data in Table 2, changing the configuration of the working zone affected both the efficiency of powder deposition and the spatial uniformity of the formed coating. For the cylindrical configuration, the highest value of η - 74.9% and the lowest value of CV_h -0.093 were recorded. This result corresponded to the lower degree of spatial heterogeneity of the electric field established in the previous subsection. Additional confirmation of this was the minimum difference between the central and geometrically shaded zones, which was 3.9 μm. For the configuration with a variable interelectrode distance, on the contrary, η decreased to 60.7%, and CV_h increased to 0.229, which reflected a simultaneous decrease in the efficiency of using the powder material and the spatial stability of the layer. In this case, the difference between the central and geometrically shaded zones reached 24.8 μm, that is, it was the largest among all configurations. The rectangular configuration occupied an intermediate position between these variants. For it, the deposition efficiency was 68.4%, and CV_h was 0.146, which reflected a moderate decrease in technological stability compared to the cylindrical variant. A characteristic feature of this case was not a sharp local deficiency of the coating, but a gradual decrease in thickness from the central areas to the periphery. The combined configuration with local shielding elements formed a different type of non-uniformity: with an average thickness close to the rectangular variant, the deposition efficiency decreased to 63.1%, and CV_h increased to 0.201. This reflected a local redistribution of the layer in a complicated working zone, as a result of which segments with a reduced thickness appeared next to the areas of increased deposition. The local increase in the coating thickness should not be considered separately from the spatial structure of its distribution. In the combined configuration and in the configuration with a variable interelectrode distance, individual central areas were characterised by higher local thickness values than in the cylindrical variant, however, this was accompanied by a weakening of the layer in the edge and shaded zones. As a result, the integral uniformity of the coating decreased, and the average thickness value could not be used as a single analytical reference point without taking into account its spatial structure. In this regard, the indicators η, CV_h and zonal thickness contrast were considered in relation to each other, and not in isolation and only as an indicator of the average layer thickness. The thickness distribution between the central, edge and geometrically shaded zones reproduced this pattern. The central zone in all configurations retained relatively higher thickness values, however, the degree of its superiority over other segments differed significantly. In the cylindrical variant, this difference remained limited, which corresponded to a more uniform nature of the deposition. In the rectangular configuration, the spatial contrast was moderate and was formed mainly due to peripheral attenuation. In the combined configuration and in the variant with a variable interelectrode distance, the central segments actually became zones of deposition concentration, while geometrically shaded or distant areas corresponded to zones of coverage deficiency. This reflected the transition of electrostatic heterogeneity into directly measured technological layer non-uniformity. The detected features corresponded to the nature of the spatial distribution of the electric field.

Configurations with lower CV_e values also showed less thickness variability, while local areas of field concentration, shielding or spatial attenuation were reproduced as areas of increased or decreased powder deposition. Therefore, spatial differences in the distribution of electrostatic action were technologically expressed in coating thickness values determined according to ISO 2808:2019 (2019) and ISO 2360:2017 (2017), as well as in powder deposition efficiency determined according to ISO 8130-10:2021 (2021). Auxiliary coating characteristics, in particular gloss and adhesion, determined according to ISO 2813:2014 (2014) and ISO 2409:2020 (2020), did not show comparable sensitivity to variations in the geometry of the working zone compared to the indicators of coating thickness and powder deposition efficiency. For different configurations of the working zone, gloss values remained close, and adhesion did not show noticeable differences, which indicated that the predominant effect of geometric variation was precisely on the spatial uniformity of the formed layer and the efficiency of powder material deposition.

Thus, changing the configuration of the working zone affected the efficiency of powder material use and the spatial stability of the formed coating. The highest value of η in combination with the lowest CV_h was found for the cylindrical configuration. The rectangular variant was characterised by moderate peripheral non-uniformity, while the combined configuration and the configuration with a variable interelectrode distance formed a more contrasting thickness distribution, but by different mechanisms: in the first case – through local shielding, in the second – through the contrast between the zones of convergence and divergence in the interelectrode space. This ratio of the indicators η, CV_h and the zonal thickness distribution determined the main technological manifestation of electrostatic differences caused by the geometry of the working zone.

Statistical confirmation of intergroup differences and the relationship between field parameters and coating thickness

Statistical analysis of the results for the spatial distribution of the electric field and the characteristics of the formed coating revealed interconfigurational differences that concerned both the field parameters and the powder deposition and uniformity of the formed coating. Checking the distribution of the main indicators using the Shapiro-Wilk test showed that the values of CV_e, η, $\bar{h}$ and CV_h did not have a statistically significant deviation from the normal distribution ($p > 0.05$), which provided grounds for further intergroup comparison. Within the comparison of the four configurations, the most pronounced statistical effects were recorded for the indicators of spatial heterogeneity of the field and spatial variability of the coating thickness, while the average layer thickness and deposition efficiency also changed between the groups, but with a lower degree of contrast. This reflected the primary influence of the geometry of the working zone on the nature of the spatial redistribution of the electrostatic action, and through it on the stability of the technological result. To verify the statistical significance of the established differences between the working zone configurations, the results of the intergroup comparison are presented in Table 3.

Table 3. Results of statistical comparison of indicators for different configurations of the working zone

Indicator	Shapiro-Wilk, p	ANOVA/t	p	The most pronounced differences between the configurations
CV_e	0.214	$F = 18.72$	< 0.001	cylindrical – combined; cylindrical – variable-distance
η, %	0.173	$F = 9.46$	0.002	cylindrical – variable-distance; rectangular – variable-distance
$\bar{h}$, μm	0.261	$F = 6.18$	0.008	cylindrical – combined; cylindrical – variable-distance
CV_h	0.148	$F = 21.35$	< 0.001	cylindrical – combined; cylindrical – variable-distance; rectangular – variable-distance
$CV_e \leftrightarrow CV_h$ (integral relation)	–	$r = 0.84$	0.001	positive relationship between field heterogeneity and thickness variability
$\bar{E} \leftrightarrow \eta$ (integral relation)	–	$r = 0.58$	0.041	moderate positive relationship

Source: compiled by the authors

As shown in Table 3, statistically significant intergroup differences were established for the key indicators of spatial field heterogeneity, powder deposition efficiency, and coating uniformity, which confirmed the influence of the geometry of the working zone on the course of the electrostatic spraying process. The most pronounced intergroup differences were recorded for the CV_e indicator. The value of $F = 18.72$ at $p < 0.001$ corresponded to a significant dependence of the spatial field distribution on the configuration of the working zone. The most clearly distinguished were the cylindrical configuration, for which the lowest CV_e value was previously established, and two configurations with increased spatial field contrast – combined and variable-distance. This result statistically reproduced the difference between a more aligned electrostatic state in a curvilinear geometry and increased spatial non-uniformity in the presence of internal obstacles or a non-constant interelectrode gap. Statistically significant differences were also established for the powder deposition efficiency indicator η. Although the magnitude of the between-group effect for this indicator was smaller than for CV_e and CV_h, the $p = 0.002$ value indicated that the change in the geometry of the working zone was associated not only with the field structure, but also with the transfer of powder material to the surface of the product. Differences were established between the cylindrical and variable-distance configurations, as well as between the rectangular and variable-distance, which was consistent with the differences in the organisation of the interelectrode space. Statistically significant differences were also established for the average coating thickness $\bar{h}$. At the same time, this indicator was less sensitive to the geometric factor than CV_h. This result corresponded to the integral nature of the average thickness, which reflected the total result within the entire sample surface, while the coating non-uniformity directly responded to local spatial deviations of the field. With this ratio, the geometric effect was manifested primarily not in the absolute change in the average thickness, but in the redistribution of the thickness between the central, edge and shaded zones.

One of the technological indicators, according to which statistically significant intergroup differences were established, was CV_h. The value of $F = 21.35$ at $p < 0.001$ indicated the dependence of the variability of the coating thickness on the geometry of the working zone. Statistically significant differences were established between the cylindrical and variable-distance configurations, between the cylindrical and combined, as well as between the rectangular and variable-distance configurations. This was consistent with the transition of spatial differences in electrostatic conditions into the non-uniformity of the formed layer. The smallest thickness variability corresponded to the configuration for which the lowest field heterogeneity was recorded, while geometries with local maxima and shaded zones were accompanied by a more uneven distribution of the coating. A generalised comparison of the indicators showed that a change in the configuration of the working zone was accompanied by a change in the spatial parameters of the electric field, and these differences were reflected in the powder deposition efficiency and the distribution of the coating thickness. The closest relationship was established for the pair of indicators CV_e and CV_h, between which a positive integral correlation was found ($r = 0.84$; $p = 0.001$). A positive relationship was also established for the average electric field strength level $\bar{E}$ and the deposition efficiency η, but of a lower strength ($r = 0.58$; $p = 0.041$). This indicated that the technological result was determined not only by the integral level of the field, but also by the nature of its spatial distribution.

The correlation between local values of electric field strength and coating thickness is shown in Figure 3.

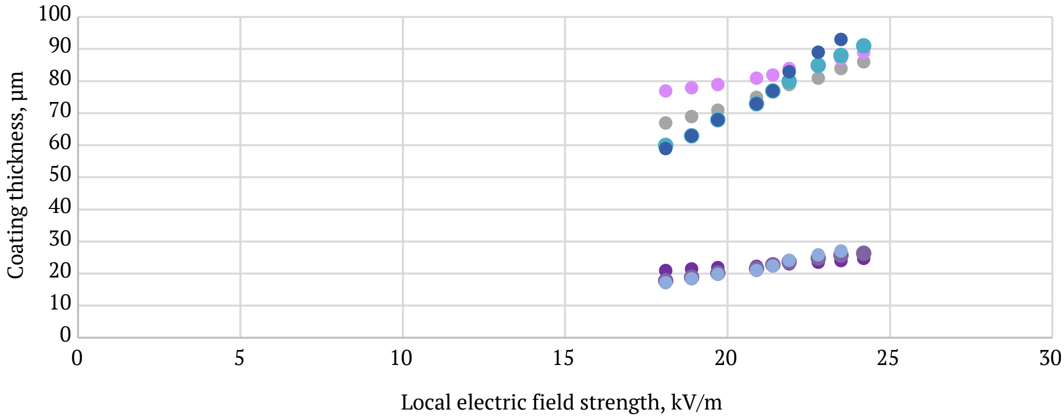

Figure 3. Correlation between local electric field strength values and coating thickness

Note: the points represent local values for different configurations of the working zone; the trend line shows the general trend of coating thickness change with increasing electric field strength strength: warm tones correspond to higher values, cold tones to lower ones

Source: compiled by the authors based on ISO 2360:2017 (2017), ISO 2808:2019 (2019)

As shown in Figure 3, a positive relationship was established between local electric field strength values and coating thickness in spatially correlated areas of the sample. The location of the experimental points for all studied configurations along the ascending trend line reflected the change in both indicators within the entire considered range. In the zone of lower local electric field strength values, smaller coating thickness values were recorded, while with increasing E, the h values also increased. The points corresponding to different configurations of the working zone formed a single trend, maintaining a certain spread relative to the trend line. Such a distribution reflected the relationship between local differences in the electrostatic state of the working zone and the thickness of the formed coating. Correlation analysis of local values of E and h confirmed a statistically significant positive relationship between these indicators: Pearson's coefficient was $r = 0.79$ at $p < 0.001$. The obtained result confirmed the presence of a relationship between the local electric field strength and the thickness of the deposited layer in spatially corresponding areas of the surface. Thus, statistical analysis showed that the differences between the studied configurations of the working zone were statistically significant for both electrostatic and technological indicators. The largest intergroup differences were established for the parameters CV_e and CV_h, which indicated a relationship between the spatial heterogeneity of the electric field and the non-uniformity of the coating. The local correlation between the electric field strength and the coating thickness showed that geometrically determined differences in the field distribution were accompanied by differences in powder deposition on the sample surface. This linked the results of electrostatic modelling with the actual spatial distribution of the formed coating.

The influence of the geometry of the working zone on the electrostatic and technological indicators of the powder coating system

The influence of the geometry of the working zone on the course of electrostatic powder coating was manifested both in the parameters of the spatial distribution of the electric field and in the technological indicators of powder deposition and coating formation. Comparison of the indicators CV_e, η, $\bar{h}$, CV_h and the thickness distribution at the control points showed that the configurations of the working zone differed not only in the intensity of the electrostatic action, but also in the nature of its spatial distribution. Electrostatic differences between the configurations were accompanied by differences in the efficiency of powder deposition, variability of the coating thickness and the presence of zones of local underspray. Within the framework of the comparison, technological indicators were associated not so much with the maximum local values of electric field strength, but with the nature of its distribution within the working volume. The generalised electrostatic and technological characteristics of the studied configurations are given in Table 4.

Table 4. Generalised comparative characteristics of working zone configurations by electrostatic and technological indicators

Work area configuration	CV_e	η, %	$\bar{h}$, µm	CV_h	Thickness distribution at control points	The expressiveness of geometrically shaded areas	Generalised characteristic
Rectangular	0.261	68.4	74.8	0.146	Moderately uneven; reduced thickness at the periphery	Moderate	Intermediate
Cylindrical	0.178	74.9	77.5	0.093	Most aligned; minimal local deviations	Minimum	Best overall balance of indicators
Combined with local shielding elements	0.311	63.1	73.6	0.201	Contrast; local reduction in thickness in shaded segments	Expressed	Increased heterogeneity
Variable-distance	0.330	60.7	71.9	0.229	Most uneven; significant difference between central and remote areas	High	Highest heterogeneity

Source: compiled by the authors based on ISO 2360:2017 (2017), ISO 2808:2019 (2019), ISO 8130-10:2021 (2021)

As shown in Table 4, the lowest CV_e and CV_h values were recorded for the cylindrical configuration, which were 0.178 and 0.093, respectively, while the powder deposition efficiency η was 74.9%. This was combined with a more uniform spatial distribution of the electric field and a smaller spread in the coating thickness. The highest CV_e and CV_h values were recorded for the variable-distance configuration, which were 0.330 and 0.229, respectively, and η was 60.7%. This configuration also recorded the largest thickness difference between the central and remote areas of the surface. For the rectangular configuration, the values $CV_e = 0.261$ and $CV_h = 0.146$ corresponded to moderate spatial heterogeneity, which was manifested mainly in the peripheral segments. For the combined configuration with local shielding elements, the values of $CV_e = 0.311$ and $CV_h = 0.201$ reflected increased heterogeneity associated with local redistribution of the field near internal obstacles. A combined comparison of the results showed that the technological indicators were associated not so much with local intensity maxima as with the nature of the spatial distribution of the field within the working volume. A decrease in CV_e was accompanied by a decrease in CV_h and higher values of η, while an increase in spatial heterogeneity of the field was combined with an increase in the variability of the coating thickness and a decrease in the efficiency of powder deposition.

Therefore, within the studied configurations of the working zone, a decrease in the spatial heterogeneity of the electric field was accompanied by an increase in the efficiency of powder deposition, a decrease in the variability of the coating thickness, and a weakening of the zonal contrast between the central, edge, and geometrically shaded areas. According to the set of indicators CV_e, η, CV_h, $\bar{h}$ and the nature of the thickness distribution for the cylindrical configuration, the lowest values of spatial field heterogeneity and coating thickness variability were recorded with the highest powder deposition efficiency at the same time. For the combined and variable-distance configurations, higher values of CV_e and CV_h were established, which was accompanied by a more uneven distribution of the coating. Thus, the spatial distribution of the electric field can be considered as an indicator related to the technological parameters of powder deposition and coating formation in electrostatic powder coating systems.

DISCUSSION

The study found that the influence of the geometry of the working zone on the technological result was realised primarily through the degree of spatial alignment of the electric field. The determining factor was not the fact of the local increase in the electric field strength itself, but the nature of its spatial distribution within the spraying zone. With less inhomogeneity of the electrostatic field, the efficiency of powder deposition increased, the variability of the coating thickness decreased, and the contrast between the central, edge, and geometrically shaded areas of the surface weakened. This result is consistent with the approach of B. Siyahhan *et al*. (2018), who linked the reliability of the numerical reproduction of the application process with the comparison of the calculated and experimental spatial distribution of the material. Within the framework of this work, this pattern is specified for powder coating systems through the interpretation of the spatial pattern of application as a consequence of the degree of electric field alignment. The revealed consistency is explained by the fact that in both cases the final state of the coating was determined not by the isolated action of a separate parameter, but by the spatially organised distribution of deposition conditions within the application zone. A similar pattern was observed when comparing the obtained results with the work of M.-R. Pendar & J.C. Páscoa (2019). In the study, it was found that the nature of the material transfer in the electrostatic field is directly related to the local distribution of the layer within the application zone. The results obtained in this work are consistent with this approach and specify it for powder coating systems, since a spatially more aligned field corresponded to higher deposition efficiency and lower variability of the coating thickness, while the contrasting electrostatic state was accompanied by local areas of insufficient powder deposition. Such consistency is explained by the common mechanism of the transition of spatial differences in electrostatic action into differences in the accumulation of powder material on the surface of the product. The study also found that the geometry of the working space changed the structure of the electric field and the nature of powder deposition even with unchanged operating parameters. A similar conclusion is given in the work of N. Guettler *et al*. (2020), where it is shown that the numerical description of electrostatic rotary atomisers significantly depended on the correct specification of the initial conditions of spraying and the parameters of the injection model. Within the framework of the work conducted, this pattern acquired a different interpretation, since it was not the input conditions of the formation of the torch that were decisive, but the configuration of the working zone in which the electrostatic interaction of the flow with the surface of the product was realised. The correspondence of the results is explained by the fact that in both cases the parameters of the spatial organisation of the process determined the final pattern of deposition, but at different levels: in one case, the conditions of the initial formation of the flow played a decisive role, in the other, the spatial conditions of its further transfer and deposition within the working zone.

Similar results are also observed when compared with the work of K. Sidawi *et al*. (2021). In it, the geometrically determined effect is associated with a change in the microgeometry of the spraying element, which restructured the atomisation conditions and the initial structure of the flow. In the study, a consequence close in physical logic was formed at a different level – due to a change in the macrogeometry of the working zone. The commonality of the conclusions is that the geometrically determined violation of the spatial symmetry of the process in both cases increased the inhomogeneity of the application. The difference is explained by the localisation of this factor: in one case, it was concentrated in the spraying unit itself, in the other – in the configuration of the working space, which determined the further conditions for the transfer and deposition of the powder material. It is advisable to consider the results on the zonal distribution of the coating thickness in a materials science context. M. Szala & E. Kot (2017), analysing the properties of polyester powder coatings after repainting, showed that the features of layer formation are important for the subsequent state of the coating as a material system. Although a direct analysis of the geometry of the working zone was not carried out in this work, such a comparison is appropriate, since in both cases the initial prerequisite for the following differences was the conditions for the formation of the coating layer. In view of this, the relationship established in the study between the geometry of the working zone, the variability of the thickness and the severity of local zones of reduced deposition can be considered as a factor that further affects the surface and operational characteristics of the coating. A comparison with works devoted to the optimisation of the application process also shows that the results obtained do not contradict the general logic of technological control, but clarify it at the level of spatial mechanisms. A.D. Karaoglan & E. Ozden (2021) linked the optimisation of electrostatic powder coating with the stabilisation of coating parameters through the rational selection of process factors. The data obtained in this work are consistent with this approach, but make it possible to specify that one of the sources of this stabilisation is the spatial alignment of the electric field. This correspondence is explained by the fact that in both cases the final technological effect was determined not by an isolated change in a separate parameter, but by the consistency of the conditions under which the coating layer was formed. The data of S. Kulothungan *et al*. (2022), who established the dependence of the material transfer efficiency on the conditions of electrostatic spraying, are interpreted in the same direction. The study shows that the increase in the spatial heterogeneity of the electric field was accompanied by a decrease in the efficiency of powder deposition. The consistency of these results is explained by a common mechanism: the spatially uneven nature of the material transfer increases powder losses and reduces the stability of its deposition on the target surface. That is why the spatial state of the electrostatic field should be considered not only as an accompanying characteristic of the process, but as one of the factors that directly determines the effectiveness of the application.

Comparison with the results of A.N. Khan *et al*. (2022) additionally showed that the target characteristics of the coating cannot be interpreted outside the spatial structure of the formation. The study found that a local increase in thickness in individual zones did not in itself provide higher uniformity of the coating as a whole. This conclusion is consistent with the approach of the aforementioned authors, who considered process optimisation through achieving the specified parameters of the coating layer. The consistency of the results is explained by the fact that local material growth does not eliminate inter-zone contrast if the spatial distribution of deposition generally remains uneven. A similar logic is also observed when comparing with works devoted to modelling the spatial structure of the torch and flow. R.I. Saye *et al.* (2023), in high-precision modelling of rotational spraying, showed the sensitivity of the process to the spatial organisation of the torch formation. Within the framework of the study, a similar result was obtained for the electrostatic field in the working zone. The consistency is explained by the fact that both the change in the spatial structure of the flow and the change in the spatial structure of the field are ultimately reflected in the local distribution of the material on the receiving surface. That is why the spatial parameters of the process should be considered as a direct prerequisite for the inhomogeneity or levelling of the coating layer.

The work of M. Scholl *et al.* (2023), in which electrostatic powder coating is considered as a technology for forming high-voltage insulation, also provides grounds for a meaningful correlation with the results obtained. Despite the different functional context, what is common is that in both cases the spatial control of the layer formation acquired a decisive importance. Such consistency is due to the fact that for coatings with specified functional properties, not only the presence of the layer itself is critical, but also the predictability of its spatial distribution over the surface.

The methodological dimension of the established results is additionally emphasised when compared with the approach of B. Christensen & M. Owkes (2023). These authors showed that a spatially detailed description of the process provides more explanation of the material distribution than integral averaged characteristics. The study revealed the same principle regarding the coating non-uniformity: it cannot be fully explained by integral indicators alone without taking into account the spatial structure of spraying and deposition. The consistency is explained by the fact that it is the spatial description that allows interpreting local differences in thickness that remain hidden when using only averaged parameters. Partial, but not complete, coincidence is observed when comparing with the results of J. Huang *et al.* (2023). In the authors' work, the improvement of the characteristics of the formed layer is associated with the use of ultrafine powder. In the study, a similar result was achieved due to another factor – the geometry of the working zone. What these approaches have in common is that a more controlled layer formation created the prerequisites for higher structural integrity of the coating. The difference is due to the nature of the control influence: in one case, the dispersion of the powder was of decisive importance, in the other, the configuration of the application space. A similar pattern is also revealed when correlated with the study by Y. Matsushita *et al.* (2024), where modelling of the painting process was used to reproduce the spatial structure of the application. Within the framework of this work, it was also established that the final distribution of the material was determined not only by the spraying mode, but also by the spatial organisation of the working zone. This consistency is explained by the fact that the spatial reproduction of the process in both cases was a necessary condition for explaining local differences in the thickness of the coating and the nature of its distribution over the surface.

The results also showed that local heterogeneity of material deposition can translate into differences in the structure and properties of the coating layer. A similar conclusion is given in the study by J. Xie *et al.* (2024), where the influence of particle size distribution on the flowability and film properties of organic powder coatings was established. Such a comparison is appropriate, since in both cases the coating properties depended on the conditions of layer formation, although the nature of the initial factor was different: in one case it was the granulometric composition, in the other – the geometry of the working zone. This confirms that the final state of the coating is determined not only by the material composition or the application mode, but also by the spatial conditions in which the powder deposition occurs. The study also showed that increasing the local electric field strength in itself did not provide the best technological result without spatial field alignment. This conclusion correlates with the results of A. Benmoussa *et al.* (2025), who showed the possibility of increasing the efficiency of electrostatic painting by modifying high-voltage conductors and using a pulsed electric field. The difference is that in the mentioned work the efficiency increased due to a change in the electrical conditions of the system, while in the results presented here, an independent role of the geometry of the working zone was traced. The mechanism itself remained common, since in both cases the control of the spatial distribution of the electrostatic action was of decisive importance, and not only the increase of individual local parameters. The results obtained also showed that the target coating thickness cannot be considered in isolation from the spatial uniformity of its distribution. This conclusion is consistent with the data of T. Šolić *et al.* (2025), who also considered the coating thickness as one of the central criteria for optimising the process parameters. In the conducted study, this indicator acquired a different analytical content, since it was evaluated not only by the average level, but also by the spatial variability and contrast between individual surface zones. The consistency is explained by the fact that in both cases the coating thickness was meaningful only in connection with the conditions of its formation, and not as an isolated self-sufficient indicator. The numerical aspect of the spatial organisation of electrostatic spraying is presented in the work of M. Herkins *et al.* (2026), devoted to the computational modelling of the electrostatic application system. Its results showed the possibility of increasing the efficiency of the process by optimising the spatial configuration and reducing losses in the flow. The obtained data are consistent with this approach, since the application efficiency was also determined by the spatial conditions of material transfer within the working zone. The coincidence of the conclusions is due to the fact that in both agro-engineering and coating applications, electrostatic spraying remains sensitive to the configuration of space, which determines the completeness of particle transfer to the target surface and the nature of the subsequent deposition.

The set of obtained results and the comparison with the data of related studies indicate that the geometry of the working zone is an independent engineering factor that determines the spatial organisation of the electric field, the conditions for the transfer of powder material and the nature of the formation of the coating layer. The established dependencies showed that the technological result in powder coating systems is determined not by the local increase of individual parameters, but by the degree of spatial alignment of the electrostatic action, on which the efficiency of powder deposition, the uniformity of the coating thickness and the severity of zones of reduced deposition depend. The revealed patterns are consistent with experimental, numerical and technological approaches, within which the spatial description of the process makes it possible to explain local differences in the application more accurately than the integral averaged characteristics. Therefore, the geometry of the working zone should be considered not as a secondary condition of the process, but as an independent factor controlling the spatial structure of the electrostatic action, through which the connection between the field parameters, the completeness of powder deposition, the uniformity of the coating and the potential quality of the formed layer is realised.

CONCLUSIONS

The study showed that the geometry of the working zone is an independent factor that determines the spatial distribution of the electric field in the electrostatic powder coating system, and through it affects the efficiency of powder deposition and the uniformity of the formed coating. A comparison of four configurations of the working zone established that a change in the shape of the working volume, the presence of local shielding elements and variations in the interelectrode distance were accompanied by a change in the spatial heterogeneity of the electric field, local zones of concentration of electric field strength and areas of its weakening. For the cylindrical configuration, the lowest value of the coefficient of variation of the electric field strength $CV_e = 0.178$ was recorded, while for the combined and variable-distance configurations this indicator was 0.311 and 0.330, respectively. For the rectangular configuration, the value $CV_e = 0.261$ corresponded to the intermediate nature of the spatial distribution of the field, with moderately pronounced peripheral weakening. This indicated that the reduction in spatial field heterogeneity was accompanied by more even electrostatic conditions within the control volume.

Technological indicators changed in accordance with the electrostatic characteristics. For the cylindrical configuration, the highest value of powder deposition efficiency $\eta = 74.9\%$, the largest average coating thickness $\bar{h} = 77.5$ μm and the smallest value of the coefficient of variation of the coating thickness $CV_h = 0.093$ were established. For the combined and variable-distance configurations, η decreased to 63.1% and 60.7%, and CV_h increased to 0.201 and 0.229, respectively. This distribution of indicators reflected the transition of electrostatic heterogeneity into technological layer non-uniformity and an increase in the contrast between the central, edge and geometrically shaded areas of the surface. Statistical analysis confirmed the significance of inter-configuration differences. The most pronounced between-group effects were established for CV_e ($F = 18.72$; $p < 0.001$) and CV_h ($F = 21.35$; $p < 0.001$). Integral correlation analysis showed a close positive relationship between CV_e and CV_h ($r = 0.84$; $p = 0.001$), and local correlation analysis between electric field strength and coating thickness confirmed a statistically significant positive relationship ($r = 0.79$; $p < 0.001$). According to the set of electrostatic and technological indicators, the most appropriate within the studied options was the cylindrical configuration of the working zone. The limitations of the study include the consideration of a limited number of geometric configurations and standard flat samples without taking into account complex-profile products and a wider range of spraying modes. Further research should be directed towards expanding the range of geometric models of the working zone, analysing spatial powder deposition on products with complex surface configurations, and combining electrostatic modelling with prediction of local coating thickness.

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REFERENCES

[1] Ayrilmis, N. (2022). A review on electrostatic powder coatings for the furniture industry. *International Journal of Adhesion and Adhesives,* 113, article number 103062. doi: 10.1016/j.ijadhadh.2021.103062.

[2] Baxevani, A., Lamprou, E., Mavropoulos, A., Stergioudi, F., Michailidis, N., & Tsoulfaidis, I. (2025). Investigation of corrosion resistance in powder-coated 6060 aluminum alloy: Effects of powder coating and pre-anodizing followed by powder coating. *Metals,* 15(10), article number 1062. doi: 10.3390/met15101062.

[3] Benmoussa, A., Pendar, M.-R., & Páscoa, J.C. (2025). Enhancing electrostatic spray-painting efficiency with modified high-voltage conductors: A numerical study on pulsed electric fields. *Journal of Aerosol Science,* 193, article number 106491. doi: 10.1016/j.jaerosci.2024.106491.

[4] Christensen, B., & Owkes, M. (2023). Efficient extraction of atomization processes from high-fidelity simulations. *Computers & Fluids,* 254, article number 105808. doi: 10.1016/j.compfluid.2023.105808.

[5] Chyhyrynets, O., Sanginova, O., Hu, J., Wu, Y., & He, X. (2025). Optimization of the composition of aluminum phosphate and walnut shell-based composition to increase the corrosion resistance of paint coatings. *Technology Audit and Production Reserves*, 4(3(84)), 12-17. doi: 10.15587/2706-5448.2025.334800.

[6] Gimenez, J.M. (2024). Multiscale simulation of electrostatic powder coating sprays. *Computational Particle Mechanics,* 11(3), 1441-1461. doi: 10.1007/s40571-023-00703-w.

[7] Gots, V.I., Kochetov, G.V., Lastivka, O.V., Samchenko, D.M., & Mehet, V.S. (2023). Corrosion resistance of powder coating with use of ferritization waste. *Modern Construction and Architecture*, 4, 49-55. doi: 10.31650/2786-6696-2023-4-49-55.

[8] Guettler, N., Knee, P., Ye, Q., & Tiedje, O. (2020). Initial droplet conditions in numerical spray painting by electrostatic rotary bell sprayers: A framework for optimization of injection model coefficients. *Journal of Coatings Technology and Research,* 17, 1091-1104. doi: 10.1007/s11998-020-00352-1.

[9] Herkins, M., Zhao, L., Zhu, H., & Jeon, H. (2026). CFD modelling of an electrostatic spraying system to optimise pesticide spray efficiency and reduce drift. *Biosystems Engineering,* 263, article number 104378. doi: 10.1016/j.biosystemseng.2025.104378.

[10] Huang, J., Yang, M., Wan, L., Tang, K., Zhang, H., Chen, J., Noël, J.J., Barker, I., Zhang, H., & Zhu, J. (2023). Ultrafine powder coating: Smooth surface, dense structure and enhanced corrosion resistance. *Chemical Engineering Journal,* 455, article number 140815. doi: 10.1016/j.cej.2022.140815.

[11] IEC TS 60079-32-1:2013+AMD1:2017 CSV. (2017). *Explosive atmospheres – part 32-1: Electrostatic hazards – guidance*. Retrieved from https://webstore.iec.ch/en/publication/60166.

[12] ISO 1514:2024. (2024). *Paints and varnishes – standard panels for testing*. Retrieved from https://www.iso.org/standard/85309.html.

[13] ISO 2360:2017. (2017). *Non-conductive coatings on non-magnetic electrically conductive base metals – measurement of coating thickness – amplitude-sensitive eddy-current method*. Retrieved from https://www.iso.org/standard/69943.html.

[14] ISO 2409:2020. (2020). *Paints and varnishes – cross-cut test*. Retrieved from https://www.iso.org/standard/76041.html.

[15] ISO 2808:2019. (2019). *Paints and varnishes – determination of film thickness*. Retrieved from https://www.iso.org/standard/71583.html.

[16] ISO 2813:2014. (2014). *Paints and varnishes – determination of gloss value at 20°, 60° and 85°*. Retrieved from https://www.iso.org/standard/56807.html.

[17] ISO 8130-10:2021. (2021). *Coating powders: Part 10: Determination of deposition efficiency*. Retrieved from https://www.iso.org/standard/80812.html.

[18] ISO 8130-13:2019. (2019). *Coating powders: Part 13: Particle size analysis by laser diffraction*. Retrieved from https://www.iso.org/standard/68405.html.

[19] Karaoglan, A.D., & Ozden, E. (2021). Electrostatic powder coating process optimisation by implementing design of experiments. *Transactions of the IMF,* 99(1), 46-52. doi: 10.1080/00202967.2020.1846349.

[20] Kasdi, A., Chouali, S., Bekakria, A., & Dascalescu, L. (2023). Experimental and numerical modeling of DC corona discharge in Wire-Cylinder-Plane configuration. *Journal of Electrostatics,* 123, article number 103814. doi: 10.1016/j.elstat.2023.103814.

[21] Khan, A.N., Goud, V., Alagirusamy, R., Mahajan, P., & Das, A. (2022). Optimization study on wet electrostatic powder coating process to manufacture UHMWPE/LDPE towpregs. *Journal of Industrial Textiles,* 51(4), 6686-6704. doi: 10.1177/15280837211070995.

[22] Korzhyk, V., Kopei, V., Stukhliak, P., Berdnikova, O., Kushnarova, O., Kolisnichenko, O., Totosko, O., Stukhliak, D., & Ropyak, L. (2025). Features of the structure of layered epoxy composite coatings formed on a metal-ceramic-coated aluminum base. *Materials,* 18(15), article number 3620. doi: 10.3390/ma18153620.

[23] Kulothungan, S., Lakshmanan, P., Krishnan, P., Palani, S., & Arumugam, A. (2022). Assessment of factors influencing the transfer efficiency in electrostatic spray coating process. *Materials Today: Proceedings,* 62(2), 1039-1044. doi: 10.1016/j.matpr.2022.04.283.

[24] Matsushita, Y., Katayama, T., Saito, Y., Matsukawa, Y., Okabe, T., Shirota, M., Inamura, T., Daikoku, M., Fukuno, J., & Aoki, H. (2024). A spray painting simulation using high-speed rotary atomizer – model development and comparison of LES and RANS. *Results in Engineering,* 21, article number 101697. doi: 10.1016/j.rineng.2023.101697.

[25] Pendar, M.-R., & Páscoa, J.C. (2019). Numerical modeling of electrostatic spray painting transfer processes in rotary bell cup for automotive painting. *International Journal of Heat and Fluid Flow,* 80, article number 108499. doi: 10.1016/j.ijheatfluidflow.2019.108499.

[26] Saye, R.I., Sethian, J.A., Petrouskie, B., Zatorsky, A., Lu, X., & Rock, R. (2023). Insights from high-fidelity modeling of industrial rotary bell atomization. *Proceedings of the National Academy of Sciences of the United States of America,* 120(4), article number e2216709120. doi: 10.1073/pnas.2216709120.

[27] Scholl, M., Vogel, N., & Lang, S. (2023). Electrostatic powder coating as a novel process for high-voltage insulation applications. *Advanced Engineering Materials,* 25(19), article number 2300465. doi: 10.1002/adem.202300465.

[28] Sidawi, K., Moroz, P., & Chandra, S. (2021). Bell-cup serrations and their effect on atomization in electrostatic rotating bell atomizers. *Experiments in Fluids,* 62, article number 180. doi: 10.1007/s00348-021-03266-9.

[29] Siyahhan, B., Boldrini, M., Hauri, S., Reinke, N., & Boiger, G. (2018). Procedure for experimental data assessment for numerical solver validation in the context of model based prediction of powder coating patterns. *The International Journal of Multiphysics,* 12(4), 373-392.

[30] Šolić, T., Marić, D., Peko, I., & Samardžić, I. (2025). Optimization of coating process parameters by analysis of target powder thickness and regression modeling. *Applied Sciences,* 15(2), article number 673. doi: 10.3390/app15020673.
[31] Subbotina, V., Sobol, O., Belozerov, V., Subbotin, A., & Smyrnova, Y. (2020). A study of the phase-structural engineering possibilities of coatings on D16 alloy during micro-arc oxidation in electrolytes of different types. *Eastern-European Journal of Enterprise Technologies,* 4(12(106)), 14-23. doi: 10.15587/1729-4061.2020.209722.
[32] Szala, M., & Kot, E. (2017). Influence of repainting on the mechanical properties, surface topography and microstructure of polyester powder coatings. *Advances in Science and Technology Research Journal,* 11(2), 159-165. doi: 10.12913/22998624/69680.
[33] Tsapko, Y., Likhnyovskyi, R., Buiskykh, N., Horbachova, O., Mazurchuk, S., Lastivka, O., Tsapko A., Sokolenko, K., & Matviichuk, A. (2023). Determining patterns in the formation of a polymer shell by powder paint on wood surface. *Eastern-European Journal of Enterprise Technologies*, 1(10(121)), 37-45. doi: 10.15587/1729-4061.2023.273364.
[34] Wang, C., Jian, X., Yang, Q., Sun, K., & Zhang, S. (2025). Theoretical and experimental study on coating uniformity in automatic spray-coating of pipeline weld repairs. *Coatings,* 15(10), article number 1193. doi: 10.3390/coatings15101193.
[35] Xie, J., Zhu, X., Shao, Y., Zhang, H., Zhang, H., & Zhu, J. (2024). An experimental and theoretical study on effects of particle size distribution on flowability and film properties of organic powder coatings. *Progress in Organic Coatings,* 195, article number 108668. doi: 10.1016/j.porgcoat.2024.108668.

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Аналіз впливу геометрії робочої зони на розподіл електричного поля в системах порошкового фарбування

Анотація. Метою дослідження було встановлення особливостей просторового формування електричного поля в системах електростатичного порошкового фарбування та його впливу на показники осадження порошку і рівномірність покриття. Методологія поєднувала стендовий порівняльний експеримент, тривимірне електростатичне моделювання системи “коронний електрод – заряджений факел – заземлений виріб”, неруйнівне вимірювання товщини сухої плівки, визначення ефективності осадження порошку та статистичний аналіз електростатичних і технологічних показників для чотирьох конфігурацій робочої зони. Установлено, що циліндрична конфігурація характеризувалася найменшою просторовою неоднорідністю електричного поля: коефіцієнт варіації напруженості електричного поля становив 0,178 проти 0,261 для прямокутної, 0,311 для комбінованої та 0,330 для конфігурації зі змінною міжелектродною відстанню. Для цієї конфігурації також було зафіксовано найвище значення ефективності осадження порошку – 74,9 %, найбільшу середню товщину покриття 77,5 мкм і найменше значення коефіцієнта варіації товщини покриття – 0,093. Для комбінованої конфігурації та конфігурації зі змінною міжелектродною відстанню ефективність осадження порошку знижувалася до 63,1 % і 60,7 %, а коефіцієнт варіації товщини покриття зростав до 0,201 і 0,229 відповідно, що відображало перехід електростатичної неоднорідності у технологічну нерівномірність покриття. Статистичний аналіз підтвердив значущість міжконфігураційних відмінностей для коефіцієнта варіації напруженості електричного поля і коефіцієнта варіації товщини покриття. Інтегральний кореляційний аналіз показав тісний позитивний зв’язок між коефіцієнтом варіації напруженості електричного поля та коефіцієнтом варіації товщини покриття ($r = 0,84$; $p = 0,001$), а локальний кореляційний аналіз між напруженістю поля та товщиною покриття - статистично значущий позитивний зв’язок ($r = 0,79$; $p < 0,001$). Практичне значення результатів полягає в можливості їх використання під час проєктування, налаштування та оптимізації робочих зон у системах електростатичного порошкового фарбування для підвищення ефективності осадження порошку та рівномірності покриття

Ключові слова: електростатичне напилення; ефективність осадження; просторова неоднорідність; міжелектродна відстань; товщина сухої плівки; коефіцієнт варіації