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CFD MODELING OF AIRFLOW VELOCITY IN AUTOMOTIVE PAINT BOOTH

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Abstract

The uniformity of airflow velocity plays important role in the paint process and has a significant impact on the quality of coated surfaces. The objective of this research is to proceed CFD analysis of paint booth with currently used and updated exhaust air systems. The results of the simulation allow to determine and compare optimal airflow velocity for different models and to recommend the best way for the company to update the paint booth, leading to the most uniform airflow possible.

Keywords: air flow velocity, CFD, paint booth.

Introduction

The quality of surface painting is one of the main factors that determine the final product's aesthetic appearance, durability and performance. In the automotive repair sector and among manufacturing companies, the demand for high-quality coatings is growing, which is why there is an increasing need to precisely control the painting process and reduce the risk of defects. Some of the most common defects in surface coatings are dust inclusions, irregularities and dirt caused by static charge, all of which are directly related to environmental conditions during painting. According to ISO 14644-1 [1], even a slight increase in airborne particles can result in surface defects. International standards such as ISO 8501 [2] and ISO 8503 [3] emphasise that clean and rough surfaces are necessary for high-quality coating adhesion, while ISO 4628 [4] establishes methods for assessing coating defects.

The air extraction rate is one of the most important parameters of a paint booth. Insufficient airflow can lead to the accumulation of contaminants and dust deposition on the painted surface, while excessive airflow can cause instability and turbulence, which increases the likelihood of defects. Therefore, it is necessary to establish air flow conditions that ensure a clean, even and stable painting process. Another significant factor is static charge, which attracts dust to the painted surface. Scientific studies show that ionisation technologies can effectively neutralise the electrostatic charge of a surface and reduce dust deposition [5, 6]. This is particularly important in automotive painting processes, where even minor surface defects can result in additional repair, repainting and labour costs.

The relevance of the topic is also determined by economic factors. Surface defects increase the need for repairs and repainting, as well as labour costs, while reducing production efficiency and increasing material consumption. Therefore, technological solutions that reduce the number of defects directly contribute to companies' competitiveness and sustainability.

In practice, the operating parameters of paint booths are often selected based on manufacturer recommendations or employee experience. However, there is a

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lack of research-based data to objectively determine the optimal air extraction and ionisation parameters. Therefore, it is important to study the influence of air ionisation and air flow parameters on painting quality comprehensively, combining experimental studies with air flow modelling.

The evolution of automotive body coating processes and modern procedures are discussed in detail in [7]. The painting and coating process can be carried out in a paint booth, which is designed to operate under stable environmental conditions with a controlled air circulation system and airflow speed. Stable airflow and pressure help to prevent paint sagging, colour inconsistency and secondary paint mist attachment. During spraying, the airflow surrounds the vehicle and removes excess paint mist and solvent vapours. For an industrial paint booth, the typical operating parameters are a pressure difference of 10–80 Pa between the inside and outside and an air velocity of 0.25–0.3 m/s [8, 9]. Finish quality improves when the airflow remains laminar. This ensures that the air moves in parallel streams, allowing the paint particles to land evenly on the surface. Turbulence should be avoided because it creates unpredictable air movement. For non-industrial paint booths, the optimal airflow velocity range is assumed to be 0.2–0.5 m/s. This airflow velocity must be sufficient to remove hazardous overspray, fumes, and particles, yet low enough to avoid disrupting the application of finishing materials.

The focus of the research presented here is a paint booth designed by JSC Scarylab for painting and coating automotive bodies and parts. CFD analysis was implemented to define the optimal airflow velocity zones for the paint booth, taking into account the current and updated exhaust air systems. The model with the highest uniformity of airflow velocity will be recommended to users as the best option for updating the paint booth.

Research goal: to investigate ways to improve surface painting quality by analysing the influence of air ionisation and air extraction speeds, and modelling air flow distribution in the painting booth using CFD analysis with Solidworks Flow Simulation.

Tasks:

- Design a prototype of a paint booth and determine the optimal airflow velocity experimentally.
- Develop a computational model of the paint booth and adapt it for CFD analysis with Solidworks Flow Simulation
- Analyze the effect of different exhaust air installations to optimal airflow velocity regions in the paint booth.
- Develop recommendations for optimal air extraction and ionization parameters that minimize the formation of dust inclusions.

Research hypothesis

It is hypothesised that air ionisation, combined with an appropriately selected air extraction speed, will reduce the quantity of dust inclusions and improve the quality of the painted surface.

1. Experimental part

Description of experimental equipment

During the study, a reduced model of a painting booth (see Fig. 1) with dimensions of 2.5×1.25×2.0 m was created to simulate real car painting conditions. The working area of the booth is 3.1 m² in size and has a volume of ~6 m³, and is intended for placing objects to be painted and for carrying out painting operations.

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The model is designed to ensure positive air pressure inside the booth and the air flows are directed vertically downwards, as is typical of industrial painting booth. The air supply system enabled the air flow rate at the painted surface to be regulated, and air removal was carried out through the floor filtration zone.

Fig. 1. Model of the painting booth

During the experiment, the air flow speed could be changed and the booth could operate in two modes: with and without air ionisation. An anemometer was used to measure the air speed at the painted surface area to ensure that the set parameters remained constant throughout the test. A car mirror housing was selected for the experiment (see Fig. 2).

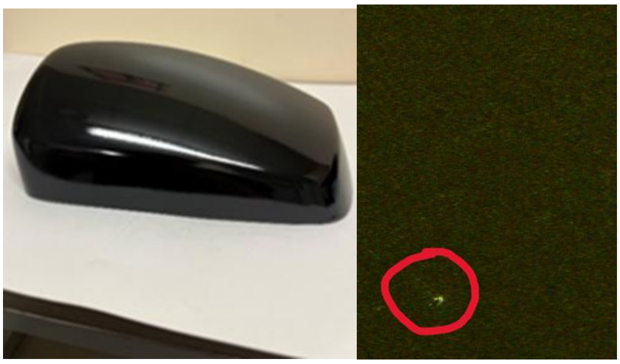

Fig. 2. Painting of the mirror housing at an airflow velocity of 0.2 m/s and dust incluse (scale ×10)

Experimental conditions

During the tests, four different air flow velocities were used: 0.2 m/s, 0.3 m/s, 0.4 m/s and 0.5 m/s. Ten samples were painted in each mode and at each air velocity. A total of 80 tests were performed: 40 without ionisation and 40 with ionisation.

The study was carried out in two experimental modes:

1) Without air ionisation to determine the natural level of dust deposition;

2) With air ionisation to evaluate the effect of the ioniser on the formation of dust inclusions.

The ionisation equipment was installed to direct the ion flow to the surface to be painted, thereby neutralising the electrostatic charge in the painting zone.

Painting process

To reduce the influence of extraneous factors on the results, all samples were painted under the same conditions. Surface preparation was carried out in

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accordance with ISO 8501 [2] and ISO 8503 [3] requirements. The same spraying distance, angle and formation of the paint layer were maintained throughout the painting process. Constant environmental conditions were also maintained, with a temperature of 20 °C and relative humidity of 40%. All tests were performed using the same equipment by the same operator to minimise the impact of human error on the results.

Quality assessment

The quality of the painted surfaces was assessed visually, based on the principles of ISO 4628 [4]. During the assessment, dust inclusions were counted within a 10 cm² area and their size and the uniformity of the surface were determined. A five-point scale was used for the assessment (see Table 1). The assessment was carried out under the same lighting conditions and at a viewing distance of 30–50 cm. Zone A, which covers the most visible part of the surface, was evaluated for each sample. The results were compared based on two main factors: air flow rate and ionisation application.

Table 1. Surface defect assessment scale

Score	Number of defects per 10 cm²	Defect size	Surface quality description
5 (very good)	0–1	very fine	The surface is even and the defects are practically invisible.
4 (good)	2–3	fine	The surface is almost even; defects are only visible upon close inspection.
3 (satisfactory)	4–6	fine–medium	single defects visible on the surface
2 (poor)	7–10	medium	Several defects are clearly visible on the surface.
1 (very poor)	>10	large	The surface is uneven with many visible defects.

Data analysis

The collected data (see Table 2) enabled us to evaluate the following:
- the effect of air velocity on the quantity of dust inclusions;
- whether ionisation reduces the occurrence of defects;
- the optimal air flow parameters for achieving good painting quality;
- whether there is an interaction between air velocity and ionisation efficiency.

Table 2. Amount of dust inclusions depending on test conditions

Airflow velocity (m/s)	Number of tests	Average quality score without ionisation	Average quality score with ionisation	Average number of defects (per 10 cm²) without ionisation	Average number of defects (per 10 cm²) with ionisation
0,2	10	4,8	4,9	0,2	0,1
0,3	10	5	5	0,2	0,1
0,4	10	4,9	4,8	0,1	0,2
0,5	10	4,8	4,9	0,2	0,1

The experimental data show that the surface quality assessment was high at all tested air flow rates, with average quality scores ranging from 4.8 to 5.0. This indicates that the experimental conditions were stable and that the painting process was carried out correctly (see Figure 3).

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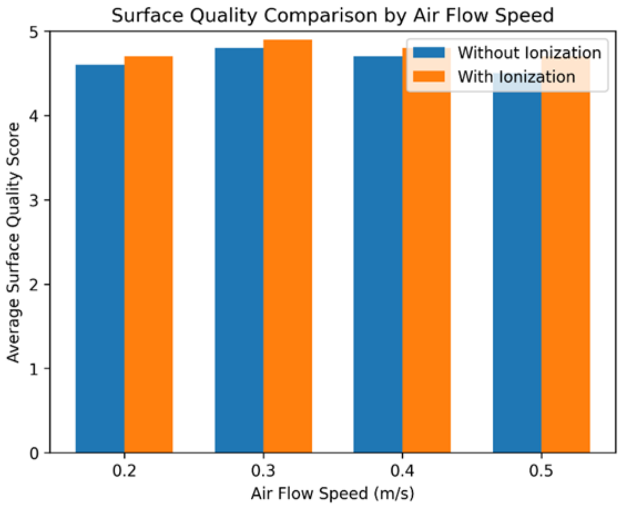

Fig. 3. Average quality score depending on airflow speed and ionisation

Analysis of the number of dust inclusions revealed that their quantity in all experimental modes was extremely low, with no more than 0.2 defects per 10 cm^2 area. This indicates that the environmental conditions in the painting booth were properly controlled.

Comparing results with and without air ionisation revealed that, in some cases, a slight decrease in dust inclusions was observed when ionisation was used. For instance, at airflow speeds of 0.2 and 0.5 m/s, the average number of defects decreased from 0.2 to 0.1 per 10 cm^2.

However, the overall difference in the results obtained in modes with and without ionisation was small. Therefore, it can be concluded that, in a well-controlled painting booth environment, the effect of air ionisation on surface quality is limited.

The highest surface quality score, an average of 5.0, was found at an air flow velocity of 0.3 m/s. This suggests that this air flow velocity may be optimal for stabilising the painting process.

2. CFD analysis of the paint booth currently in use

Different computational fluid dynamics (CFD) softwares are used to study natural and forced ventilation systems in building [10-14]. CFD is an effective way of reducing the time required for testing. The advantage of SolidWorks flow simulation is that it is fully integrated into the mechanical design software and allows internal and external, turbulent and laminar, steady-state and transient flow modeling [15-21].

The company exploatates downdraft paint booth for painting and coating of automotive body and parts. The geometry and main dimensions of the paint booth are shown in Fig. 4.

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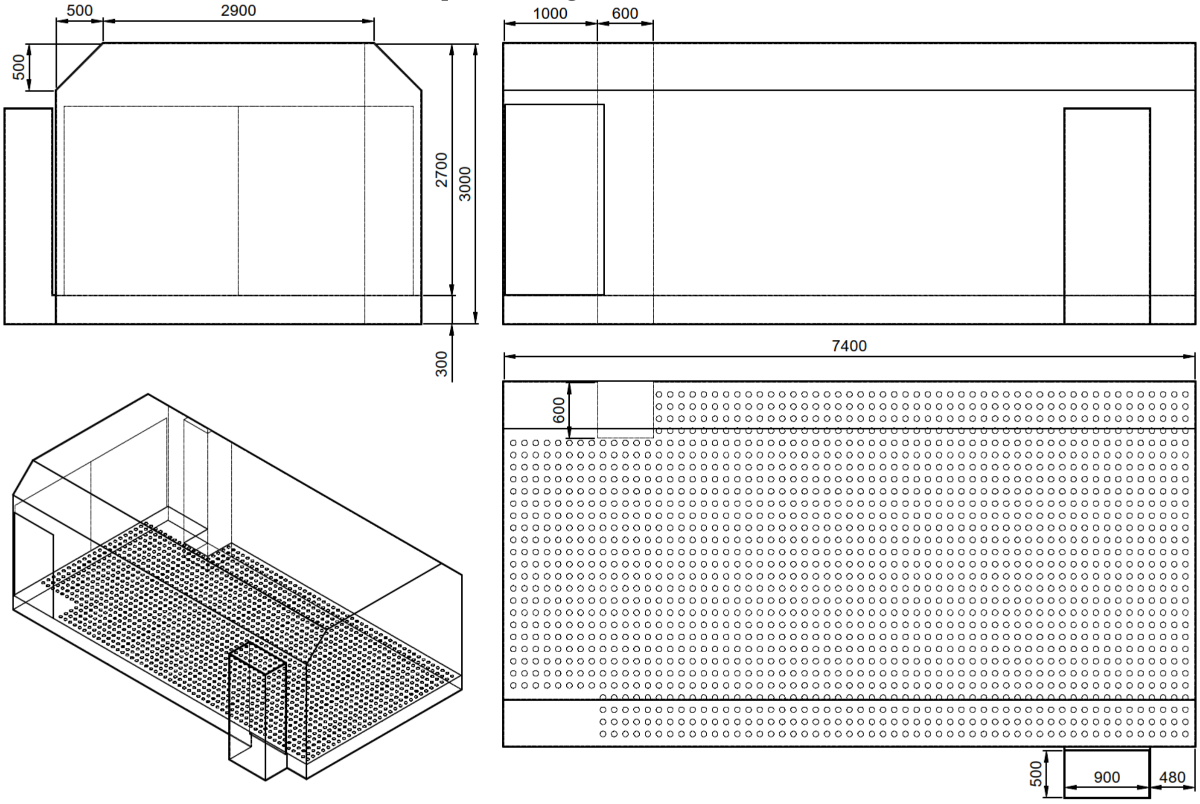

Fig. 4. Paint booth under the study

The paint booth consists of three sections – upper (air inlet), middle (process room) and lower (air exhaust). The area of air inlet is 13.6 m^2. it is covered with a sintepon-type material, which is used as an additional filter and as a airflow resitance element. The area of the process room used for paint and curing is of 28.5 m^2 and the volume is ~75 m^3. Exhaust air section is connected to a rectangular exhaust duct (0.9×0.5 m). Air flow from the booth to exhaust air section occurs through Ø60 mm openings of the steel plates on the booth floor.

3D CAD model of the empty paint booth designed in the Solidworks software (model TK) is shown in Fig. 5. The model is used for CFD analysis in SolidWorks Flow Simulation. Some elements of the booth are simplified; for example, the floor steel plates are designed without stiffening edges and some elements are omitted (door, gates and lamps). These changes do not have significant affect to the accuracy of the study results. However, the column and the dimensions of the ducts were maintained.

In CFD analysis the main volume of process room is meshed with default global automatic mesh function, because in this volume the airflow is slow and uniform. The airflow velocity increases while transversing through a narrow openings of the floor. In this region, the Local mesh with refinement level 4 is used. The resulting mesh on two orthogonal cuts is shown in Fig 6.

The fluid of room temperature air (T=293.2 K) is used for simulation. It is assumed that a uniform overpressure is created by the supply fan over the inlet area (A_{in} = 13,6 m^2). Thus, the constant velocity v_{in} = 0.37 m/s is applied to the inlet seeling face and the atmospheric pressure (p_0=101325 Pa) is applied to the outlet duct face (A_{out} = 0,45 m^2).

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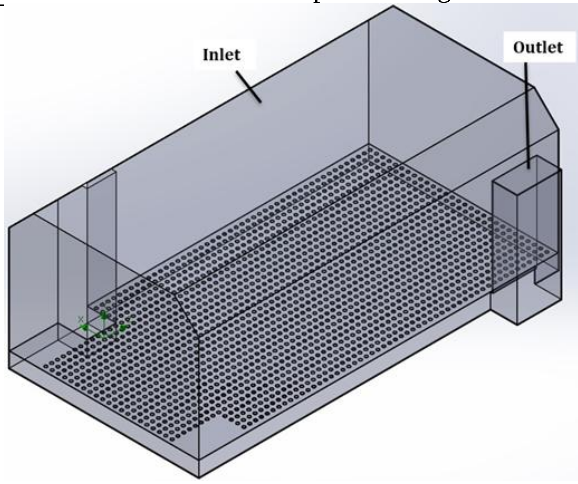

Fig. 5. 3D CAD model (model TK)

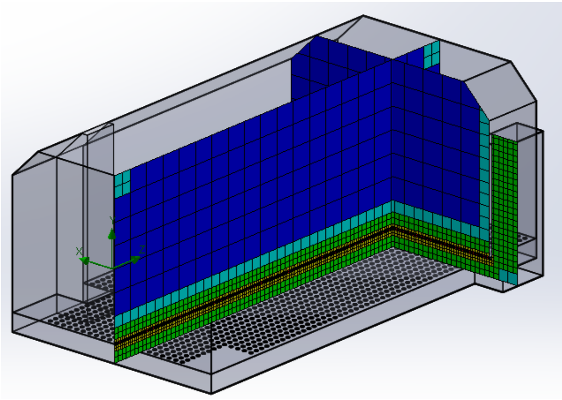

Fig. 6. Mesh visualisation (model TK)

Fig. 7 shows simulation results of airflow velocity for model TK. Two horizontal planes at a height of 0.5 m and 1 m from the floor (planes h0.5 and h1) are used to present velocity contour plots. The compliance of the paint booth with requirements for air flow velocity range is relevant at some distance (0.4 m) from the walls, so the useful region for paint process in horizontal plane presents the rectangle 6.6×3.1 m with an area A_{UR}=20.3 m^2 (see Fig. 8). This region is mostly used to place objects to be painted and to have free passage around it for operators.

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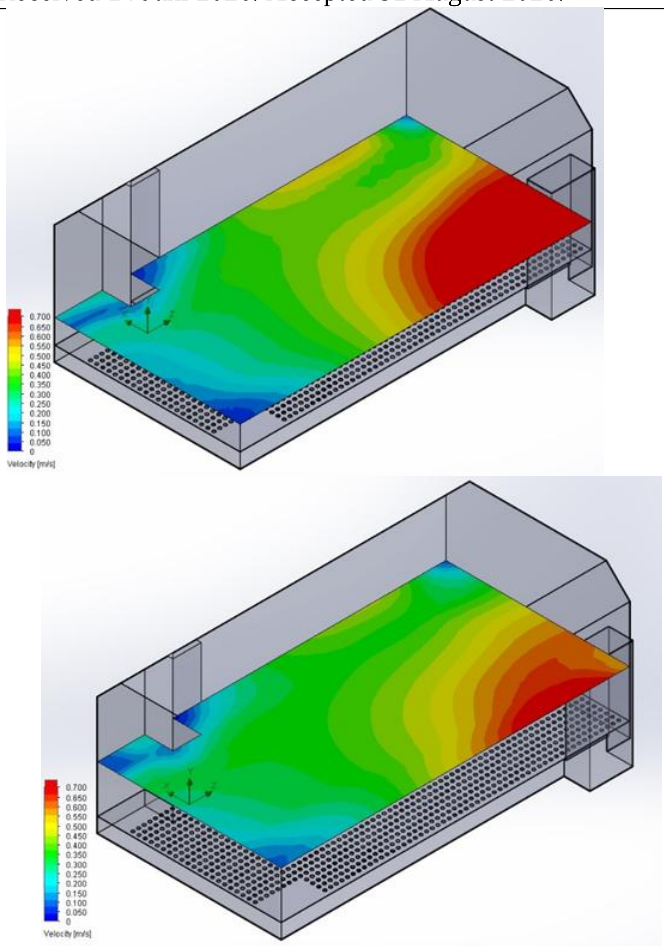

a b

Fig. 7. Simulation results of airflow velocity (model TK): a - plane h0.5; b – plane h1

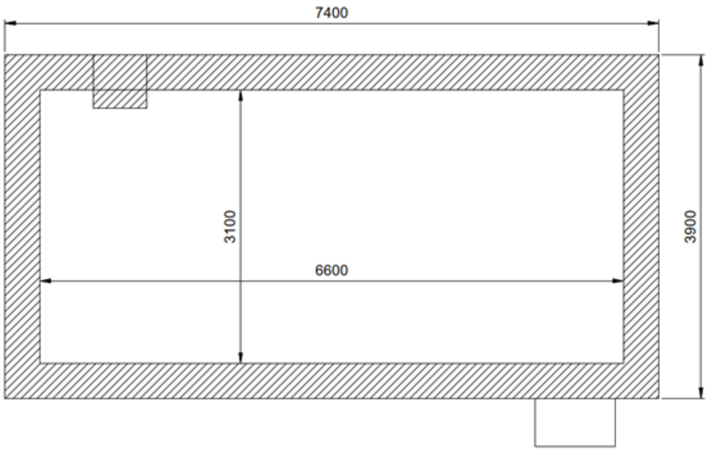

Fig. 8. Dimensions of useful region for paint process in the booth

Fig. 9 illustrates optimal airflow velocity regions in the planes h0.5 and h1. At a height of 0.5 m from the floor in the front part of the booth the air velocity is less than 0.2 m/s, and in the rear part of the booth (near the air outlet) there is a large area with air velocity greater than 0.5 m/s. It is obvious that the position of the outlet duct influences such a distribution of air flow velocities. At a height of 1 m from the floor the uniformity of airflow rate increases significantly ($\bar{A}_{0.2-0.5} = 80.8$ %).

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Airflow velocity analysis shows that the air inlet of the paint booth is designed optimally. However, the air outlet should be redesigned to increase optimal airflow velocity region.

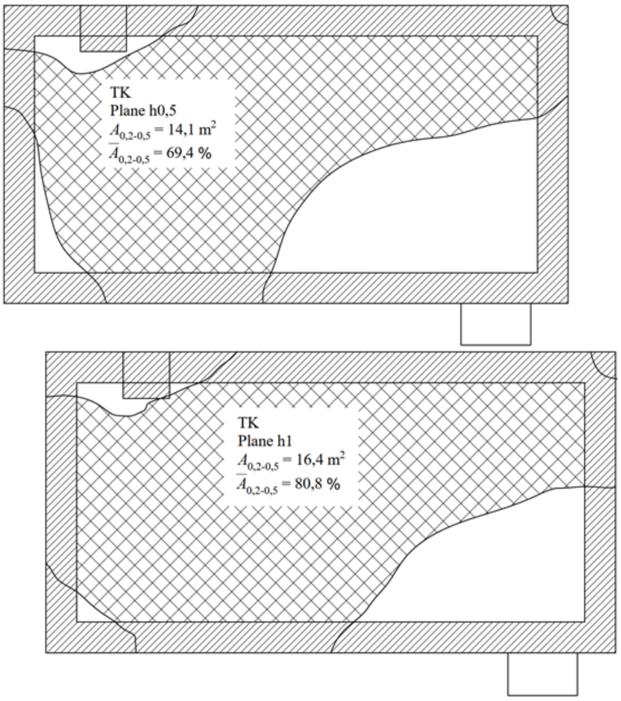

Fig. 9. Optimal airflow velocity regions (model TK): a - plane h0.5; b – plane h1

3. CFD analysis of the paint booth with updated exhaust system

Unfortunately, there is no technical possibility of designing an exhaust air duck on both sides of the paint booth. Therefore, the following options should be explored:

- Installation of an exhaust duct in the middle part of the paint booth (model TK1)
- Installation of additional exhaust duct closer to the front part of the paint booth (model TK2).

3D models of the paint booth with updated air outlet (TK1 and TK2) are shown in Fig. 9. The same inlet and outlet boundary conditions were set for new models: inle velocity $v_{in} = 0.37$ m/s, outlet pressure $p_0 = 101325$ Pa.

Fig. 11 and 12 shows airflow velocity contours for model TK1 and TK2 in planes h0.5 and h1. In Fig. 13, the graph of calculated optimal airflow velocity areas $\bar{A}_{0,2-0,5}$ for all models are presented. In Fig. 14, the graph of pressure drops Δp between inlet and outlet determined by CFD analysis for all models is shown.

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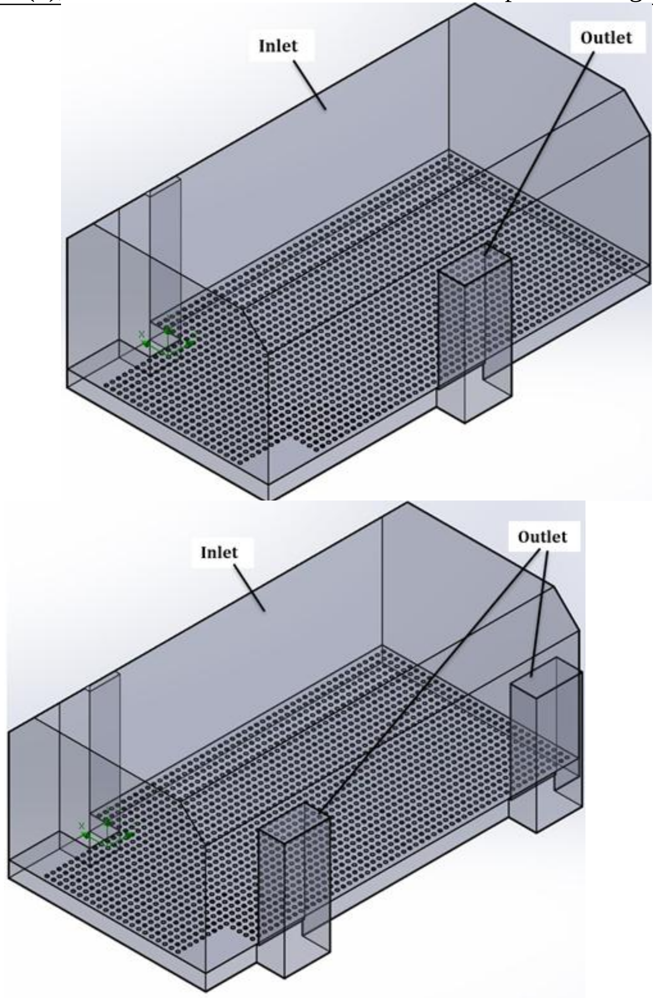

a b

Fig. 10. Paint booth: a – model TK1; b – model TK2

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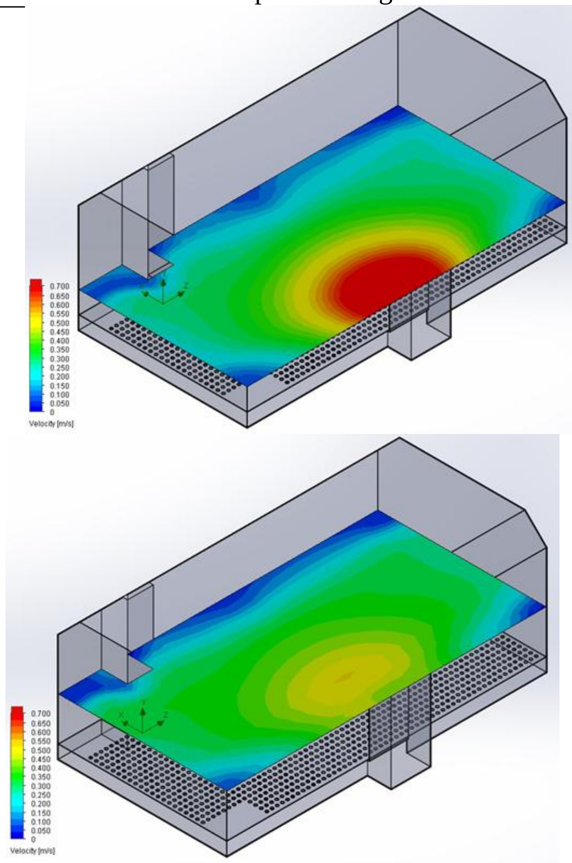
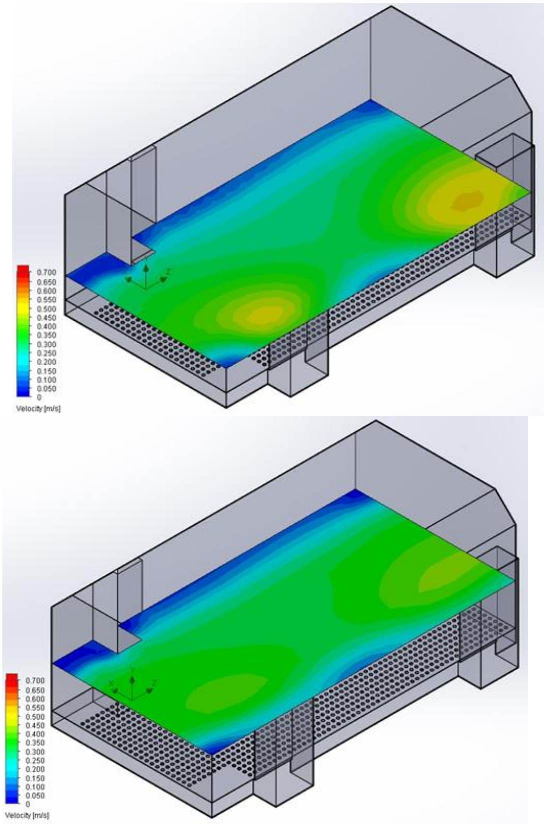


a b

Fig. 11. Simulation results of airflow velocity (model TK1): a - plane h0.5; b – plane h1



a b

Fig. 12. Simulation results of airflow velocity (model TK2): a - plane h0.5; b – plane h1

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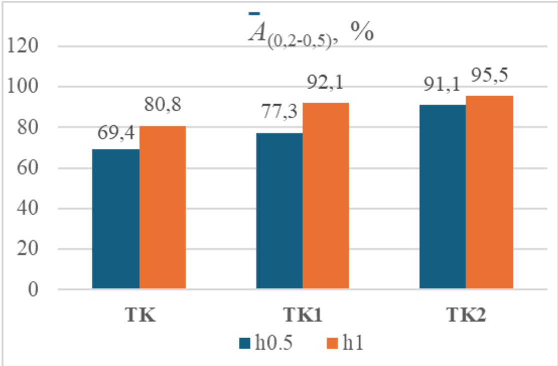

Fig. 13. Optimal airflow velocity area $\bar{A}_{0,2-0,5}$ (models TK, TK1 and TK2)

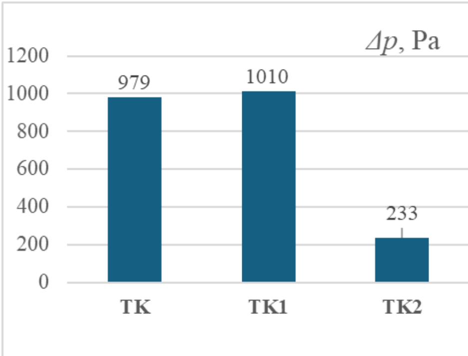

Fig. 14. Pressure drop between inlet and outlet (models TK, TK1 and TK2)

The CFD analysis of currently used paint booth (model TK) shows lowest relative areas $\bar{A}_{0,2-0,5}$ and only in plane h1 it slightly exceeds 80%. In this case, the left rear corner of the booth should be avoided for placing an object to be painted due to airflow velocity higher than 0.5 m/s.

The simulation results for model TK1 are better than for TK: the airflow speed in the booth is more uniform, but the relative area $\bar{A}_{0.2-0.5}$ in the plane h0.5 is still less than 80%. In this case, an area with a higher airflow velocity (>0.5 m/s) appears in the middle of the booth, near the outlet duct. This is not beneficial for the painting process since painted objects are often positioned in the central region of the booth. However, in the h1 plane, the airflow can be considered fully developed and steady; here, the value of $\bar{A}_{0.2-0.5}$ is 92 %.

The simulation results for model TK2 are the best since in both planes (h0.5 and h1) the area $\bar{A}_{0.2-0.5}$ exceeds 90 %. The airflow is uniform throughout region A_{UR}. and there are no regions with an airflow velocity greater than 0.5 m/s. In addition, Fig. 12 shows that using two outlet ducts significantly reduces pressure drop by more than four times, which makes it possible to reduce ventilation system energy costs.

The simulation results show that updating the paint booth by installing an additional exhaust duct (according to the TK2 model) is appropriate. This update can be easily implemented at minimal financial cost and, most importantly, it increases the uniformity of airflow velocity throughout the painting process area.

4. Conclusions

1. The experimental data obtained show that the surface quality rating was high at all airflow velocities tested, with average quality scores ranging from 4.8 to 5.0. A

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comparison of the results with and without air ionization revealed that, in some cases, a slight reduction in dust inclusions was observed when ionization was used. However, the overall difference in results between modes with and without ionization was small, so it can be concluded that, in a well-controlled spray booth environment, the effect of air ionization on surface quality is limited.

2. CFD analysis using SolidWorks Flow Simulation was performed on three different paint booth models to determine the airflow velocity uniformity rate in two horizontal planes, one at a height of 0.5 m and the other at 1 m from the floor.
3. The calculated values of the optimal relative airflow areas show that the airflow uniformity of the existing paint booth (model TK) is low, particularly in plane h0.5, where $\bar{A}_{0,2-0,5}$ is less than 70 %. Installation of exhaust duct in the middle part of the paint booth (model TK1) improves airflow uniformity in plane h1, but in plane h0.5 it is still less than 80 %. Airflow uniformity of paint booth with additional exhaust duct (model TK2) is best because in planes h0.5 and h1 the relative area $\bar{A}_{0,2-0,5}$ is bigger than 90 %.
4. Recommendations for the paint booth user: the paint booth should be updated by installing additional exhaust duct according to the model TK2. This would increase the optimal airflow velocity region and reduce ventilation energy costs.

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