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Piotr NIKOŃCZUK

PRELIMINARY MODELING OF OVERSPRAY PARTICLES SEDIMENTATION AT HEAT RECOVERY UNIT IN SPRAY BOOTH

WSTĘPNY MODEL SEDYMENTACJI OSADÓW LAKIERNICZYCH W REKUPERATORZE KABINY LAKIERNICZEJ*

Overspray sediments settling on the recuperator's fins cause operational problems. The cross sections of the recuperator's channels gradually decrease and finally it result in clogging of the recuperator. The layers of sediments cause air flow resistance and also heat transfer resistance. The paper presents preliminary results of sedimentation process modeling. The model of overspray creation takes into account a droplets size and particles concentration in air stream inside extraction ducting. Simulation results are compared with measurements conducted in three commercial spray booths.

Keywords: *spray booth, sedimentation, overspray, overspray sediments.*

Odkładające się na lamelach rekuperatora osady lakiernicze powodują problemy eksploatacyjne. Przekroje poprzeczne kanałów rekuperatora stopniowo zmniejszają się i ostatecznie prowadzi to do zatkania rekuperatora. Oprócz oporów przepływu powietrza osady stanowią również opór termiczny przy wymianie ciepła. W artykule przedstawiono wstępne wyniki modelowania procesu sedymentacji drobin lakieru. Zaprezentowano model powstawania mgły lakierniczej zawierającej krople lakieru o określonej średnicy oraz stopień koncentracji drobin lakieru w kanale wentylacyjnym za filtrem. Wyniki symulacji porównano z wynikami pomiarów w rzeczywistych kabinach lakierniczych.

Słowa kluczowe: *kabina lakiernicza, sedymentacja, mgła lakiernicza, osady lakiernicze.*

1. Introduction

During the operation of the spray booth in the painting mode, the air in the spray booth is constantly replaced. Worn, warm air is ejected from the work space of the cabin. In case to increase Energy efficiency of spray booths the heat recovery units are used. The most popular are cross recuperators. Construction of recuperator consists of fins, which separate alternately streams of hot and cold air. Distance between fins is within range of 12 – 15 millimeters. In figure 1 is shown a diagram with the location of the cross heat exchanger in typical booth assembly.

The hot air includes overspray particles. Droplets of paint create sediments on internal parts of exhaust ducting. Sediments are also created on recuperator fins. In figure 2 is shown recuperator contaminated with overspray sediments.

Growing sediments cause resistance of heat flux and air flow [14, 15]. Finally the layer of sediments causes clogging of recuperator. It results in spray booth being inoperative because of explosion hazard.

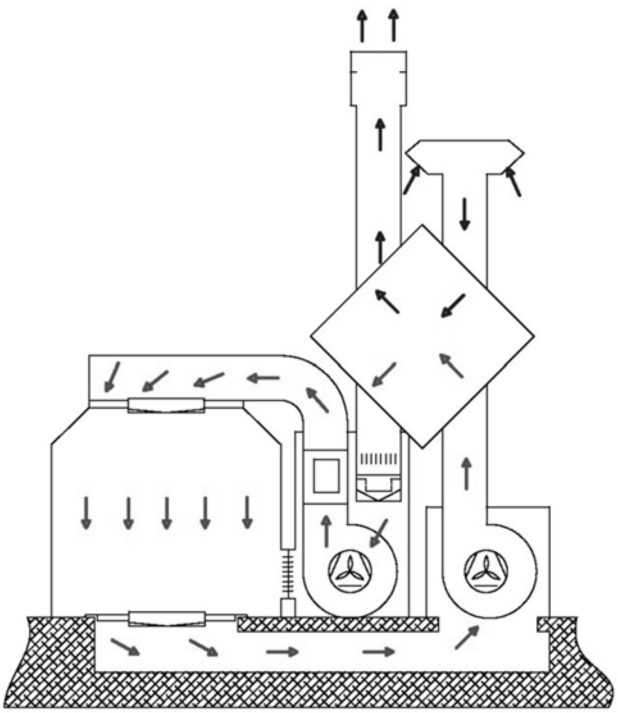

Fig. 1 A location of the heat exchanger in typical booth assembly

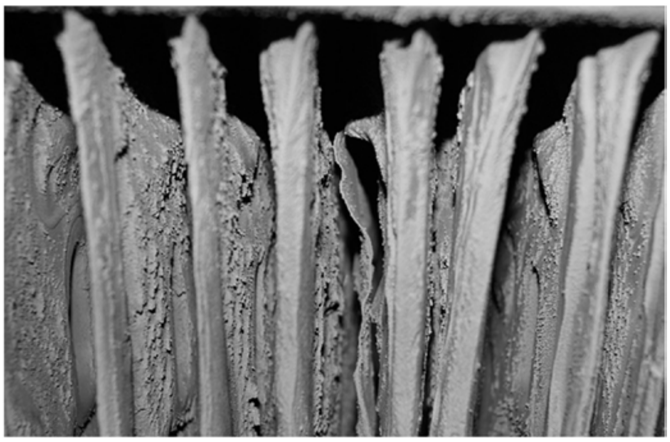

Fig. 2 Recuperator fins contaminated with overspray sediments

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl***

Assessment of the risk of explosion in the spray booth is shown in [24] in relation to the powder paint shop.

The issue of the impact of deposits on the operating conditions of technical objects is present in many areas of concerns include internal combustion engines [1, 23]. In the area of spray booths, the problem of deposits was treated negligibly due to cross sections of ventilation ducts of the order of 0.8 – 1 [m]. A few-millimeter sediment layers do not have a significant impact on changing the air flow resistance in the exhaust channels. Only the appearance of recuperators in booth ventilation systems has caused the phenomenon of sedimentation of the paint overspray visible. In the technical and operational documentation of paint booths with recuperators, the need to clean up recuperators is often neglected. No limiting conditions have been defined in relation to the thickness of the deposits and the minimum cross-section of the channel in the recuperator. The limit states allow determining the exploitation time as in the case of hot water-pie [17] or engine crankshafts [21]. The volume of the used paint has a significant impact on the thickness of overspray sediments; however, it takes on variable values during the operation of the spray booth. This requires determining fixed intervals between technical inspections of the recuperator or adopting a quasi- periodic strategy [8].

There are conducted research on the atomization of varnishes [19] and the transfer efficiency of paint spray guns [18, 22]. Regulations and recommendations regarding transfer efficiency are issued by using low-pressure HVLP (High Volume Low Pressure) spray guns [26, 27]. Publications on the size of the paint mist consider it primarily in health and environmental aspects. There are also many publications on the effectiveness of paint stop filters [4, 6, 7], other media [10, 12] or alternative methods [20, 25]. However, they do not include aspects of the impact on the operational conditions of the spray booth. The problem of atomization and transfer efficiency is also an extensive issue in the field of agricultural spraying [9, 11], and [13].

Mathematical and simulation models of sedimentation of particles on the inner walls of the channels in turbulent flow are presented in [2, 3] and [5]. This article presents a preliminary mathematical and simulation model of overspray sediments growth. The developed model takes into account the adhesive properties of drops of paint. The growth rate of the sediments layer is determined on the basis of the booth working time in the painting mode and the flow rate volume of the applied lacquer.

2. The phenomenon of overspray aggregation

During paint application, from spray gun flows a stream of paint volume $\dot{V}_P$ in form of droplets of varied size. Droplet diameters are associated with many parameters, for example: nozzle size and spray gun settings, compressed air pressure, volume of paint stream, distance between nozzle and coated surface [19]. The largest part of paint particles deposit on painted surface and create coating. The rest of paint drops fly around painting area and create overspray. The overspray is extracted from working chamber together with exchanged air. The volume of paint in overspray $\dot{V}_P^I$ depends on transfer efficiency *TE*:

$$\dot{V}_P^I = \dot{V}_P\left(1 - TE\right) \tag{1}$$

Transfer efficiency describes volume of coated paint ratio to total volume of used paint. It is non dimensional value.

Extracted air is treated by *paint stop* filter. The filter usually is located on the floor or in the wall of spray booth. Filter efficiency F_E describes arrested particles ratio to total quantity of particles. It is percentage value. Filter efficiency is depended on particles diameter [4, 7, 6, 10, 12, 20]. Suppliers of *paint stop* filters declare filter efficiency in given range [30] or average value [29]. Finally the volume of paint after filtration $\dot{V}_P^{II}$ can be described by equation:

$$\dot{V}_P^{II} = \frac{\dot{V}_P^I\left(100 - F_E\right)}{100\%} \tag{2}$$

The concentration of paint droplets degree p_c at the stream of extracted air $\dot{V}_A$ after cleaning by paint stop filter can be calculated by equation:

$$p_c = \frac{\dot{n}_p}{\dot{V}_A} \tag{3}$$

where $\dot{n}_p$ describes a stream of paint particles [1/s]. In case to find a quantity of particles n_p can be used an obvious dependence, that volume of sprayed paint is equal to total volume of all droplets of paint.

$$V_p^{II} = \sum_{i=1}^{n_p} \frac{1}{6}\Pi d_i^3 \tag{4}$$

where d_i means a diameter of *i*-particle [m]. Assuming that all paint particles have a normalized diameter d_A, the stream of paint particles can be determined from the following equation:

$$\dot{n}_p = \frac{6\dot{V}_p}{\Pi d_A^3} \tag{5}$$

A normalized diameter of paint particles d_A depends on atomization conditions and distance between nozzle and coated surface. The stream of particles is expressed in units of number of particles per second [1/s].

3. A general model of particle deposition in turbulent flow

There are conducted researches on sedimentation of particles in turbulent flow [2, 5]. A stochastic model of particles deposition and clogging of ventilation duct was proposed in four elementary stages [3]: deposition, resuspension, agglomeration and clogging. In figure 3 are shown individual stages.

The model of particle deposition on the surface is described by energy. It is described by the energy balance in the normal direction to the wall. It consists of two basic mechanisms: the hydrodynamic transportation of particles in the turbulent flow, and the mechanism of adhesion. Adhesion is based on the physicochemical interactions between the two solids. The particles are deposited on the wall (or on already attached particles) when their energy in the normal direction to the wall is sufficient to overcome the reflection energy barrier, or otherwise bounce off the surface. The energy barrier is determined using the DLVO theory [3], named after the authors Derjaguin-Landau and Verwey-Overbeek. The theory assumes that total energy is the sum of the energy of interaction:

$$U_{part-surf} = U_{part-plate}^{DLVO}\left(1 - S_{\text{cov}}\right) + \sum U_{part-part}^{DLVO} \tag{6}$$

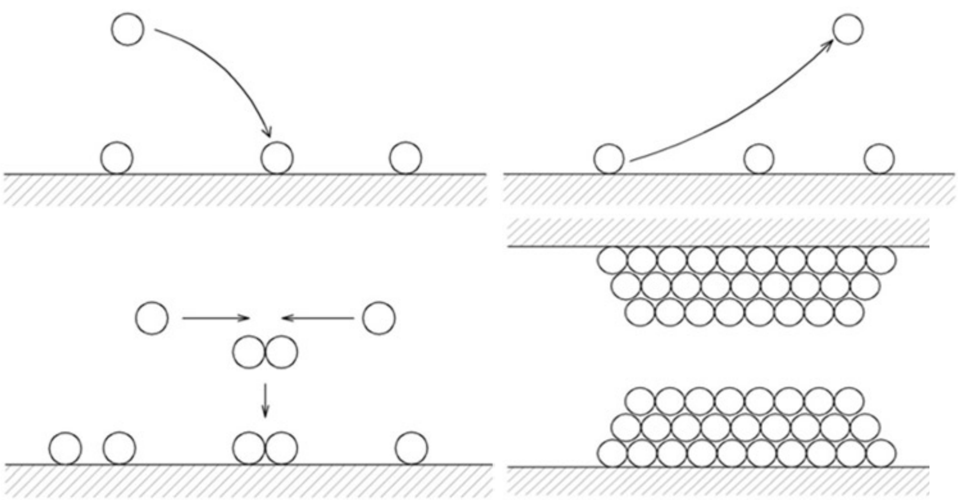

Fig. 3. Elementary stages of deposition model a) deposition, b) resuspension, c) agglomeration, d) clogging

where S_{COV} denotes the surface coverage of embedded particles, the $U_{part\text{-}plate}$ means interaction between the particle and the clean surface. $U_{part\text{-}part}$ denotes the interaction between the particles. Contact area S_{cont} specifies the contact area and is given by dependency:

$$S_{cont} = \Pi\left(2\sqrt{d_{part}d_{dep}} + d_{dep}\right)^2 \tag{7}$$

where d_{part} is the radius of particles and d_{dep} radius of embedded particles. If the contact zone are previously embedded particles present, is randomly selected molecule is deposited on the next random account.

Due to the phenomenon of adhesion of paint droplets, it has been recognized that in the model of sedimentation of paints practically there is no phase of resuspension. If the particle clings to the surface, it stays there indefinitely. Two additional phenomena were proposed in the modified model: the possibility of agglomeration on the surface and the surface leveling effect. Agglomeration on the surface consists of the possibility of moving the particle by a distance equal to its diameter to another, previously settled particle. Leveling refers to the case where the drop lands on another early deposited particle to form a further layer of sediment. When in the vicinity of the drop' embedding the drop there is no particle located lower than one layer below, the particle falls to the close position in the lower layer. Agglomeration and surface leveling can take place only at the moment of deposition of particle and this can only take occur within an area of radius equal to the diameter of the drop's diameter.

4. Simulation model

For the proposed model a numerical model was developed. Adopted the geometry of the duct of the recuperator shown in figure 4. The recuperator is dedicated to the paint booth with an air flow volume $\dot{V}_A = 5.56\ [m^3/s]$ (20 000 [m^3/h]) [28]. Its construction consists of channels of width $w_d = 1\ [m]$, high $h_d = 0.012\ [m]$ and length $l_d = 1\ [m]$. Altogether there are 120 channels alternately for warm and cold air.

For simplicity, it is assumed that the diameter of a droplet of paint d has a normalized constant value. The surfaces of the recuperator fins and the space between them were separated into a three-dimensional grid consisting of cubes, having sides equal to the diameter of the particles. In figure 5 is shown a 3D spatial grid and particles of diameter d.

A steady stream of paint $\dot{V}_P = 3.33e\text{-}6\ [m^3/s]$ (200 [ml/min]) was assumed. With such a volume of paint and the spray gun nozzle distance from the coated surface equal 0.3 [m] can be assumed normalized mean droplet of lacquer equal to $d = 10^{-4}\ [m]$ [19]. The flow volume of air exchanged inside paint booth had a value $\dot{V}_A = 5,56\ [m^3/s]$ (20 000 [m^3/h]). Paint transfer efficiency $TE=0,65$ was established on the basis of the European Union guidelines [26] recommending the use of low-pressure guns HVLP. The filter efficiency $F_E = 94\ [\%]$ was adopted on the basis of one of the catalogs of filter distributors [30].

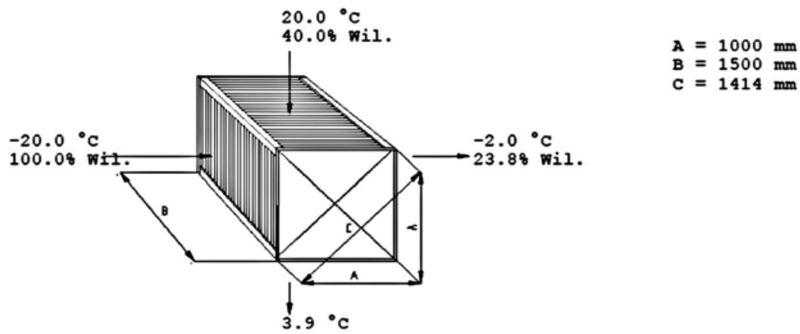

Fig. 4. Recuperator dedicated for spray booth [28]

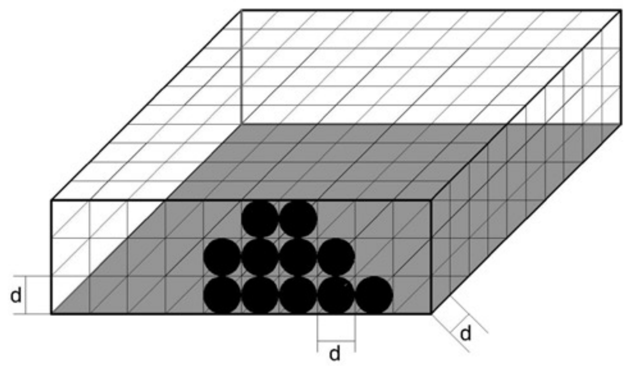

Fig. 5. A model of 3D mesh for numerical simulations

For these parameters, the average velocity of the air flow between the fins is $u = 7.7\ [m/s]$. For this speed the Reynolds number assumes the value $Re = 10828$ and indicates the turbulent flow. On the basis of generally known equations, the height of the boundary layer δ_x for turbulent flow can be determined [16]:

$$\delta_X = \frac{0.376x}{\mathrm{Re}_x^{\frac{1}{5}}} \tag{8}$$

where x is the distance from the edge of the channel while Re_x describes the local Reynolds number at point x at the speed of the undisturbed flow of u_∞ *[m/s]*:

$$Re_x = \frac{u_\infty x}{\upsilon} \quad (9)$$

The small channels of above presented recuperator require a separate, special analysis of the boundary layer. This is due to the ratio of the length of the sides of the cross section of the single duct. According to equations (8) and (9) the thickness of the layer in half the length of the channel ($x = 0.5$ *[m]*) is equal $\delta_x = 0.0159$ *[m]*. Considering that the channel height is $h_d = 0.012$ *[m]*, the height of the boundary layer cannot exceed the height of the channel. For simplicity, it was assumed that at the entire volume of exchanged air the degree of particle's concentration p_c is uniform in a turbulent flow. This also applies to the boundary layer. Similar simplification was also applied in other sedimentation models [3]. The degree of concentration of paint particles p_c describes to the amount of paint drops per 1 square meter of the air flow. In the modeled spatial grid, the thickness of the boundary layer is equal to the normalized particle diameter d. The degree of concentration of droplets p_c^I of paint in the boundary layer per square meter can be determined by the dependence:

$$p_c^I = p_c d \quad (10)$$

A one iteration of the process simulation was assumed as period of one second. The total number of the particles appearing in the boundary layer during given time τ is connected with the air flow rate:

$$n_p = \int_0^\tau p_c^I F_s u_A dt \quad (11)$$

where u_A is the average velocity of the air and F_s is the surface area of the recuperator fin on which particles are deposited.

$$u_A = \frac{\dot{V}_A}{F_d} \quad (12)$$

The cross section of the ventilation duct F_d is the product of its height h_d and the width w_d. In the model, the pressure drop in the cross section of the F_d channel was neglected.

5. Simulation results

A number of simulations have been performed for the above parameters. The results of the calculations were considered in particular in terms of the increase in the coverage of the lamella surface in successive iterations, the number of growing layers and the mean sediment height. he present results relate to the formation of deposits on the fins constituting the two channel walls recuperator width $w_d = 1$ *[m]*. The side walls of height $h_d = 0.012$ *[m]* were neglected. In figure 6 is shown a part of the resulting matrix representing the agglomeration of overspray particles after *1e6* iterations. The coordinates in Figure 7 relate to the size of the grid shown in Figure 6. In view of the above, the agglomeration of the particles exhibits a part of lamella surface. The size of presented area is equal 4e-3 x 4e-3 [m]. The highest number of layers of sediment is equal 3, which means that maximum height of the local agglomeration has value 3e-4[m].

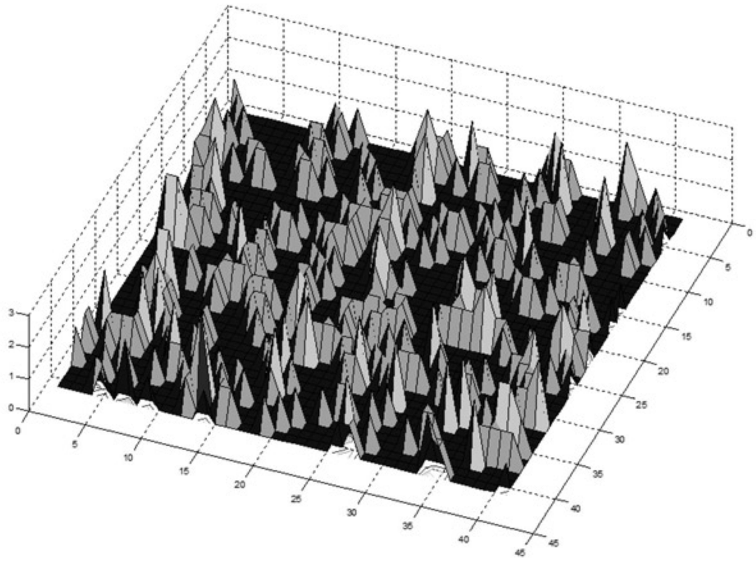

Fig. 6. Agglomeration of overspray particles after 1e6 iterations

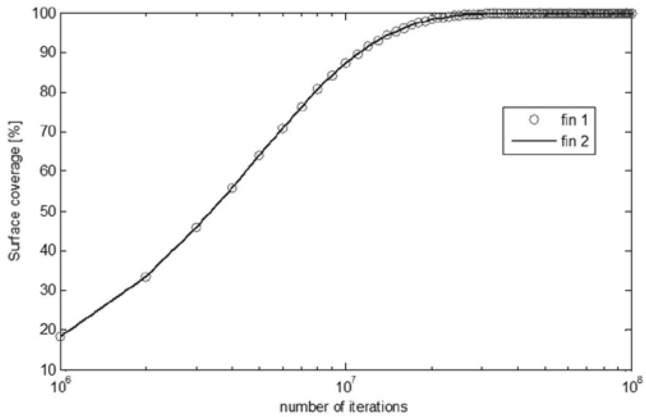

Fig. 7. Coverage of fins in subsequent iterations

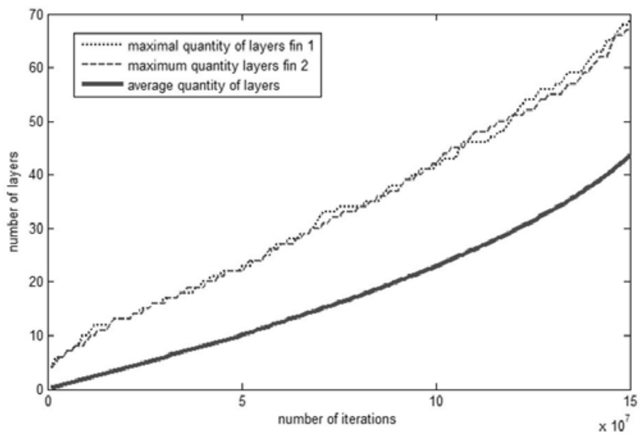

Fig. 8. Maximal and average number of layers in subsequent iterations

The degree of surface coverage after 1e6 iterations is relatively small. It does not reach 20% f total area. In figure 7 is shown the increase of the surface coverage of two fins of recuperator in subsequent iterations. Coverage close to 100% in both cases occurs after 12e7 iteration.

The maximum and average number of layers of sediments on the lamellas in subsequent iterations is shown in Figure 9. The maximum

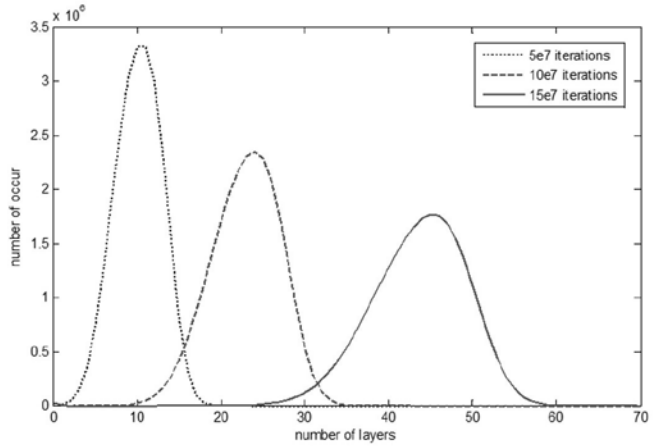

Fig. 9. Distribution of the number of layers in agglomerations after selected iterations

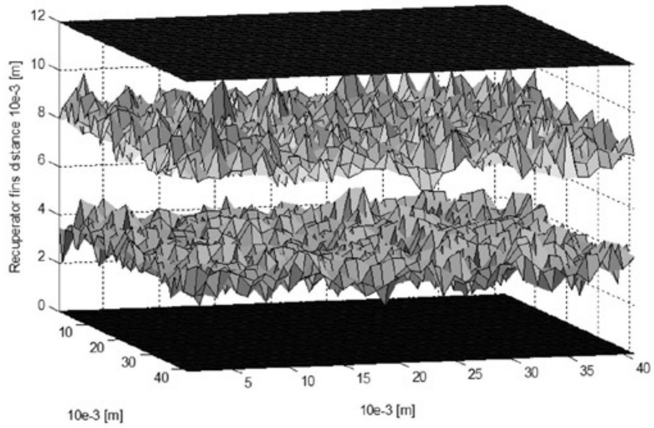

Fig. 10. Sediments on recuperator fins after 12e7 iterations

values of the layers are not much different, while the mean values for both lamellas are the same.

In Figure 8 is shown the maximum number of layers, while in the Figure 9 is presented the change in the distribution of the layers number of sediments in the chosen iterations of agglomeration. For comparison 5e7, 10e7, and 15e7 iterations were selected.

As mentioned, the coverage of the slats reaches a value close to 100% after 12e7 iteration. Figure 10 shows the visualization of sediment concentration in the space between the two lamellas after the 12e7 iteration. The visualization shows a part of fins of the same size as in Figure 6. The average height of sediments on upper and lower fins has a value of 3e-3 [m]. This results in a half reduction of the cross section of the recuperator channel.

One iteration of the simulation relates to one second of spray booth operating in paint application mode. A comparison of numerical experiment and results of real experimental work [15] is presented in Figure 11. The values deviate significantly from each other.

The simulation results indicate a much slower rate of growth of sediments compared to the results of the real measurements. In the simulation model, the recommended values of the transfer efficiency *TE* and the maximum efficiency of the filter F_E were assumed. The efficiency of the filters can be varied [29, 30]. The results of studies conducted in the wood industry presented in work [22] show that the actual transfer efficiency with HVLP guns is within the range of *TE* = 20-60%. It depends on the type of material used, the spray gun quality and condition, the geometry of the surface to be covered and the skills of the painter. In Figure 12 are shown simulation results for

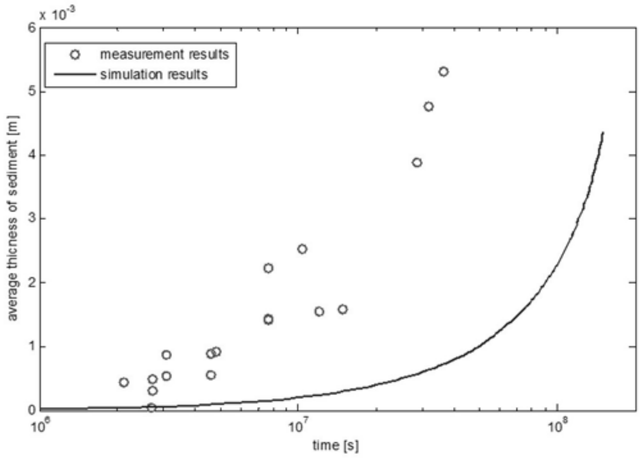

Fig. 11. Comparison of simulation and measurements results

different transfer efficiency values *TE = 0.20* and *TE = 0.55* and filter efficiencies $F_E = 80\%$ and $F_E = 85\%$ [29]. It is also taken into consideration that the total working time of the paint booth t_t is the sum of the coating times t_p, drying time t_c and ventilation time t_v [15]. It was assumed that the share of painting time t_p is half of the total time t_t.

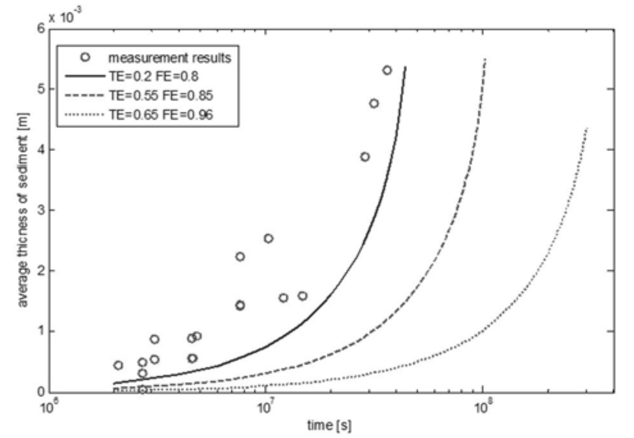

Fig. 12. Results of measurements and simulations for different transfer efficiency TE and filter efficiency F_E

The presented results concern the preliminary model of sedimentation of paint particles on the recuperator fins. Several simplifications were used. The values obtained in numerical simulations were compared with the measurement results at the three paint booths [15]. Simplification of standardized droplet diameter *d* in overspray was applied. The distribution droplet diameter depends on parameters such as the type of paint material, the spray gun nozzle size, air pressure, the volume flow of paint and the distance from the nozzle [19]. The share of paint time t_p in the total operating time of the paint booth t_t is also varied at every coating process.

6. Conclusion

Manufacturers and suppliers of heat recovery units for paint booths are often do not put in the technical manual requirements for inspection and cleaning of recuperators. he main objective of the model of sedimentation of spray mist particles being developed is to create a simplified dependence of the sediment growth rate on the averaged parameters of transfer efficiency *TE*, filter efficiency F_E and the share of painting time t_p in the total working time of the booth t_t. On the basis of the presented model, taking into account the above parameters, it is possible to pre-determine the working time of the spray booth, after which the recuperator should be cleaned. Assuming that the average thickness of the overspray sediment in the recuperator cannot exceed 1mm, then according to Figure 12, this takes place on average after 5e6 seconds. Therefore, the recuperator needs to be cleaned up at average intervals equal to 1389 operating hours of the spray booth. Taking into account the annual working time of 2000 hours for an eight-hour working day, this means an eight-month interval between the purifications of the recuperator. The growth rate of sediments is not uniform and takes individual values in different spray booths. These differences are presented in paper [15]. For safety reasons, considering the variance of growth rate, the time between inspections of the recuperator should not be shorter than 6 months. The presented period of paint booth operation between the purifications of the recuperator is based on a simplified and averaged sedimentation model. These include the mean droplet size distribution of paint depending on the properties of the material used paint, the spray gun and distance from the nozzle [19]. For the individual case, the efficiency of the F_E filter used in the cabin depends on the particles size [7] statistics of the working time of the booth in painting mode, time of spray gun operation and volume of applied paint. The above sedimentation model also allows prediction of the recuperator's contamination based on the volume of the coating material V_p used inside the spray booth.

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Piotr NIKOŃCZUK
West Pomeranian University of Technology
Faculty of Maritime Technology and Transport
Al. Piastów 41, 71-065 Szczecin, Poland

E-mail: piotr.nikonczuk@zut.edu.pl