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Examination of the Airflow Uneven Distribution over the Combine Harvester Cleaning System

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ABSTRACT

The research aims to study the uneven distribution of airflow created by a fan over the cleaning system of a combine harvester, affecting the efficiency of the technological process of separating impurities from the original crop. The article presents a methodology for studying the actual operation process using a digital twin, reveals problem areas and studies even distribution of the airflow at the outlet of the fan discharge channel of the combine harvester cleaning system. During the research, several parameters were defined. Based on the digital twin development and study, the airflow rate at the outlet of the radial fan discharge duct of the combine harvester (CH) cleaning system at different rotation rates of the fan wheel (450-1050 min^{-1}) was determined. Experimental measurements of the airflow distribution over the working part of the sieve shoe for the existing cleaning system and modern combine harvesters made up 3.75-10.2 m/s.

1. INTRODUCTION

The existing air-type sieve cleaning systems of combine harvesters have significant disadvantages. Thus, the quality of the process of separating the grain heap from impurities is not satisfactory [1-4]. Among possible reasons are increased throughput, incorrect adjustments, uneven crop maturity, uneven grain heap distribution when cleaning, different concentrations of particles (grains and impurities), humidity and impurities in the grain heap, uneven distribution of grain heap across the sieve shoe during mount harvesting. The uneven airflow distribution over the sieves is due to the combined harvester cleaning system imperfect design and the lack of a complete theoretical description and methods for justifying their design and technological parameters [1-3, 5-27].

For increasing the fatigue life of the combine harvester cleaning system, Badretdinov and Nasyrov [27] proposed a method for analyzing the fatigue life and an optimization method for the cleaning system design. The developed model of the cleaning system dynamics helped obtain the key factors affecting the fatigue life of the main components of the cleaning device.

Korn and Herlitzius [12, 13] described in their research the possibility of applying the associated CFD-DEM approach to simulate the process of separating grain from impurities in the cleaning device of a combine harvester. The complexity of the separation process is due to several interrelated factors, a wide range of properties typical for biogenic particles. Therefore, a strategic approach to creating a reliable simulation model is required. The numerical results proved the applicability of the numerical method by comparison with the corresponding experiments in general. Moreover, possible deviations underline the need for further research to improve parameterization and simulation.

Mirenko [18] studied the relationship between the combined harvester cleaning system effect and its influencing factors. A model of the rate of losses for cleaning and the parameters of the cleaning system was established. The results of the cleaning efficiency of each group under different combinations of conditions were checked. The direct and indirect relationship between the cleaning loss rate and the parameters at each operating state of the experiment was analyzed. The experimental data obtained helped predict the loss rate for several sets of factors.

Miu and Kutzbach [20] conducted experimental studies using a cleaning system model with various design and technological parameters (grain material supply, fan speed, sieve gaps).

The technological process of air-type sieve separation of grain heaps from impurities using the CH (combine harvester) cleaning system can be mathematically described as a complex system of two-phase airflow, taking into account the forces of gravity, friction and inertia [4-8, 11-13, 15, 19, 21, 22, 26]. In this case, the airflow created by the fan is one phase, and the other is solid particles, i.e., elements of the grain heap with different concentrations of physical and mechanical properties (mass, density, geometric dimensions, humidity, elasticity, sailing capacity, etc.) [5]. The differences between the phases determine the nature of the interaction between the airflow and the particles. The inertia and sailing capacity of the particles (heavy particles are seeds, light ones are chaff) result in different trajectories of their movement. Due to the aerodynamic drag force, which is greater than the force of gravity, light particles are separated by the airflow due to the difference in the air and particles velocities (particles hovering velocity). Grain material (heavier particles) mostly move (separate from light particles) under the influence of gravity and inertia of the sieves, while the aerodynamic drag force is insignificant [1-3, 8-10, 12-14, 16-18, 20, 21, 23-27].

Purpose of the research. The research uses a digital twin and aims to study the influence of the uneven distribution of airflow created by a fan over the cleaning system of a combine harvester on the efficiency of the technological process of separating impurities from the original crop.

Formulation of the problem. Unfortunately, many agricultural enterprises carry out harvesting in violation of agrotechnical requirements, which leads to significant harvested crop losses (Figures 1 and 2) and high costs [2, 4, 6].

Figure 1. Ploughed field after grain harvesting (green stripes are losses behind the harvester)

Figure 2. Large losses after harvesting

Increasing the efficiency of separation using air-type sieve systems is possible by creating a rational airflow in their chamber. The airflows' structure and the distribution of their velocities over the sieves mainly depend on the design and type of the fan and its air duct (discharge channel) [3, 7, 11, 13, 19, 22].

The task is to evaluate the operating mode of the radial fan at various technological parameters, to study the airflows in the fan neck, their distribution above sieves during air-type sieve cleaning of the combine harvester.

The research method includes bench tests of existing radial fans using the model of the air-type sieve cleaning of a combine harvester, multi-factor analysis, modelling of the airflows at the outlet of the fan discharge channel, and their subsequent distribution over the sieves using a digital twin.

The uneven distribution of the airflow over the channel of the air-sieve part of the combine harvester cleaning system suggests the need to reduce the airflow velocity in the sieve area for reducing grain losses after cleaning, thus slowing the process of separating small particles and affecting the quality of separation [2, 4-7, 11-13, 15, 19, 22].

2. MATERIALS AND METHODS

A three-dimensional solid-state model of a classical radial fan was developed using the standard CAD program COMPASS 3D v-19 to study and calculate the technological process of operation (airflow distribution over the combine harvester cleaning system) (Figure 3). For numerical implementation, the model is then imported (in STL or VRML format) to the CAE program of the FlowVision CFD complex (3.12.01), which is based on the numerical solution of the Navier-Stokes equations using the Boussinesq approximation approach in a three-dimensional problem statement using various turbulence models, taking into account the viscosity and compressibility of the medium.

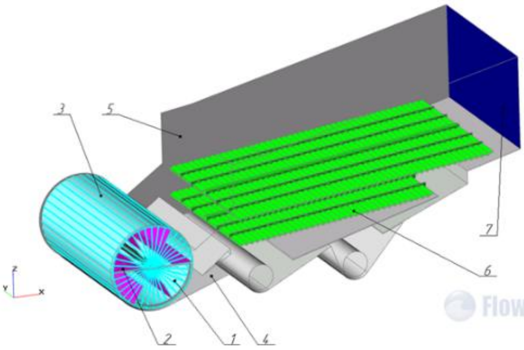

Figure 3. Calculation area of the model with boundary conditions: 1 – airflow inlet, 2 – fan blades (rotating wall), 3 – sliding surface (movement or rotation), 4 – wall, 5 – symmetry, 6 – sieve shoe (motion or oscillation), 7 – free exit

Using the FlowVision preprocessor, the required mathematical model is selected for the created calculation subdomain. The model physical parameters are set, and the boundary conditions are determined [5, 6]. The incompressible liquid simulates gas flow at large (turbulent) Reynolds numbers and small density changes. A digital twin of a real fan is created. The air movement between the rotating blades mounted on the fan wheel shaft and in the fan discharge channel (snail) is simulated in the digital twin. For modelling the surface rotations in the computational domain, in which the outer boundary is not the surface of rotation around the corresponding axis of rotation (the body), it is necessary to divide the geometry into several subdomains. So, the outer boundaries of the subdomain in which the rotation will be set must represent the surfaces of rotation around the corresponding axis. The subdomains are connected by *a moving coupling condition*, which allows modelling the air movement through the boundaries of the subdomains, taking into account the rotation of the rotating subdomain relative to the stationary one.

FlowVision allows considering the rotation of surfaces in the selected coordinate system. Besides, the standard and tangential components of the rotation speed are also taken into account. *A local coordinate system* relative to which the *rotation* will occur should be created. The boundary condition sets the *rotation* on the rotating surface. The angular velocity (rad/s) and the guide axis (x, y, z) should be specified.

Physical model: create *Substance* (load it from the standard database of substances), select *air*, and *Phase – Gas (equilibrium)*. Select *an external phase* and add *Substance-air-gas (equilibrium)* to it. In phase properties *Physical Processes phase*, we specify: *Motion*-The Navier-Stokes Model, *Turbulence* – a standard k-e model designed for modelling flows with small pressure gradients. The initial data such as *Ripple* and *Turbulence scale* are set for the phase (0.01 m in this case).

Based on the 3D model, using the boundary conditions "Wall with slip" in a rotating coordinate system, the calculation was performed in the FlowVision software package (3.12.01). When calculating the model in the FlowVision software package, the airflow generator is a radial fan; the blades create the airflow when the fan wheel rotates (revolutions 450-1100 min^{-1}).

3. RESULTS

The study of the operation of the fan of the combine harvester cleaning system was carried out in the FlowVision software package by reference to the conditions of the even airflow velocity at the outlet of the discharge channel according to the fan velocity curve and performance.

The calculations of the digital twin of the combine harvester cleaning system (Figures 4 and 5) using the FlowVision 3.12.01 software package show that the airflow is distributed unevenly along the discharge channel at the fan outlet. As a result, the quality of the grain heap separation suffers, and grain is lost.

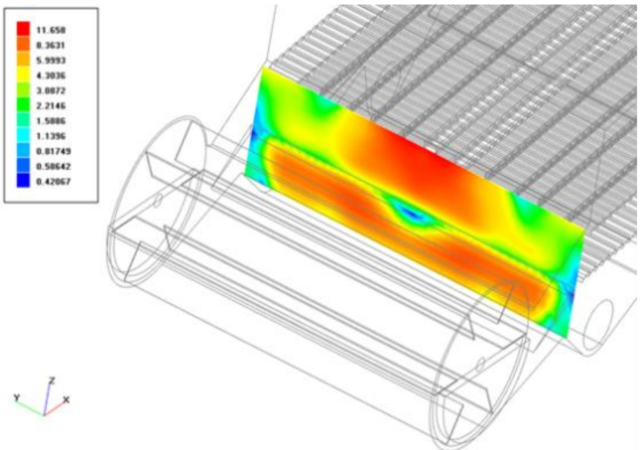

Figure 4. Results of the calculation of the airflow at the outlet of the fan discharge channel (rotation speed is 57.6 rad/s) of the CH cleaning system (distribution of the airflow velocity by filling)

Table 1. Results of the calculation of the CH cleaning system at different fan speeds

Fan speed, min^{-1}	Airflow velocity at the fan outlet, m/s		
	Minimal	**Maximal**	**Average value**
450	0.17	8.48	5.29
550	0.42	11.66	5.63
650	0.09	15.17	8.25
750	0.23	20.55	8.57
850	0.86	23.65	9.88
950	0.11	22.11	11.04
1050	0.62	26.56	13.21

Figure 4 shows that the distribution (by filling) of the airflow velocity over the discharge channel at the fan outlet is uneven. The maximum values of the airflow velocity are in the centre, and the minimum values are at the edges. Calculations for various technological parameters (fan wheel speed) were made using a digital twin (Table 1).

The calculation results (Table 1 and Figures 4, 5) prove that at different fan wheel speeds, the airflow distribution at the outlet of the discharge channel is different. If there are vortices, the airflow is either concentrated in the centre or split into two flows and moves along the edges, as in Figure 5.

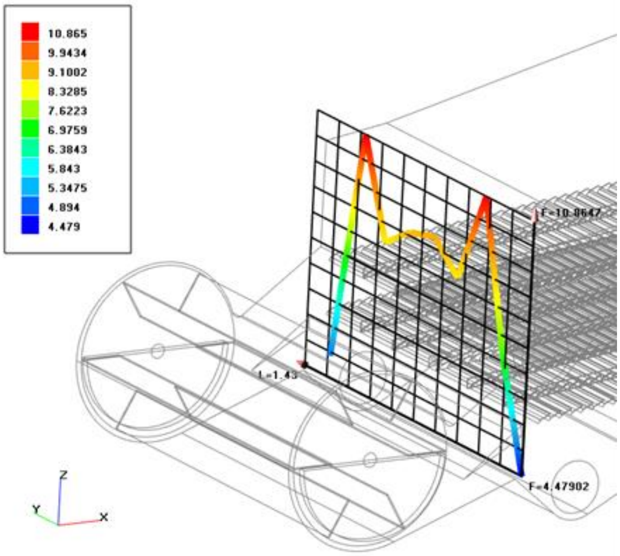

Figure 5. Diagram of the airflow velocity distribution at the outlet of the fan discharge channel of the combine harvester cleaning system (rotation speed is 78.5 rad/s)

The calculation results (Table 1) prove that the unevenness of the airflow velocity at the outlet of the discharge channel increases with an increase in the fan speed. There is also a substantial deviation from the minimum to the maximum value of the airflow velocity.

Visualization of the airflow velocity trajectories obtained from the modelling and calculation results using the FlowVision software package (Figure 6).

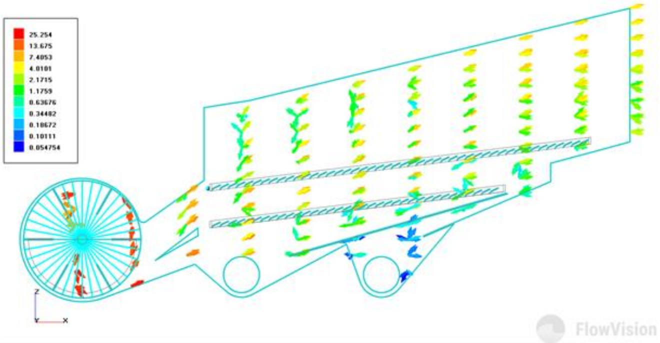

Figure 6. Trajectories of the airflow velocity vectors in the combine harvester cleaning system

Figure 6 shows that the airflow created by the fan passes through two sieve shoes. The main airflow portion moves to the scalping shoe. Another part of the airflow is cut off by a horizontal flow-divider valve (highlighted in dark blue) installed at an angle to the horizon in the fan discharge channel. It directs the airflow to the lower sieve shoe, where the airflow velocity is lower (about 3 m/s) than the airflow directed to the scalping shoe.

In the front part of the scalping sieve shoe (1/3 of the surface), the airflow velocity is much higher (up to 13 m/s) than on the remaining surface of the sieve shoe and varies in the range of 0.09-7.5 m/s. Figures 7 and 8 show that the distribution of the airflow over the sieve area is uneven with a strong gradation. The colour palette clearly shows it. The airflow is stronger in the centre (the airflow velocity is 2.2-8.6 m/s), and it is weaker at the edges (0.2-2.2 m/s). There are also vortices.

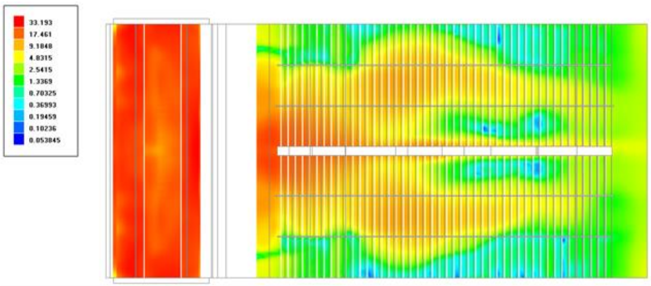

Figure 7. Calculation results: the distribution of the airflow by filling over the existing combine harvester cleaning system (at a fan speed of 89 rad/s)

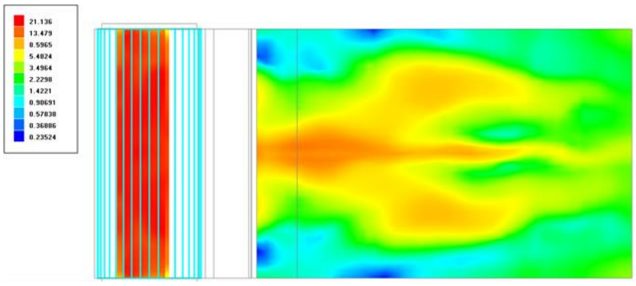

Figure 8. Calculation results: the distribution of the airflow by filling over the scalping sieve over the combine harvester cleaning system (at a fan speed of 68 rad/s)

On the one hand, high airflow rates in the centre contribute to the high-quality separation of light impurities (husk, chaff). On the other hand, full-fledged good seeds can also be blown out (release, loss) against agrotechnical requirements. At the edges of the sieve shoe, the airflow is distributed much lower than in the center. In these areas, light impurities are sometimes not separated, which is also not good since they get into the grain tank and then to the grain cleaning, which leads to an additional load upon the grain cleaning and sorting machines.

The calculation result of the airflow vectors distribution over the existing combine harvester cleaning systems at a fan speed of 57.6 rad/s is shown in Figure 9. The red circles indicate where the vortices above the scalping sieve, mainly in its front part (1/3), are visible (Figure 6, side view).

Figures 10 and 11 show the results of the digital twin of the combine harvester cleaning system and the distribution of the airflow velocity vectors over the boundaries of the scalping shoe. The calculations were performed at a fan wheel rotation speed of 68 rad/s and a simultaneous oscillatory motion of the sieve shoe.

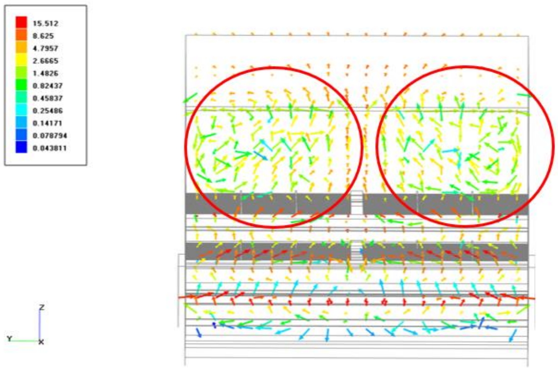

Figure 9. Calculation results: airflow distribution (velocity vector) over the combine harvester cleaning system (front view)

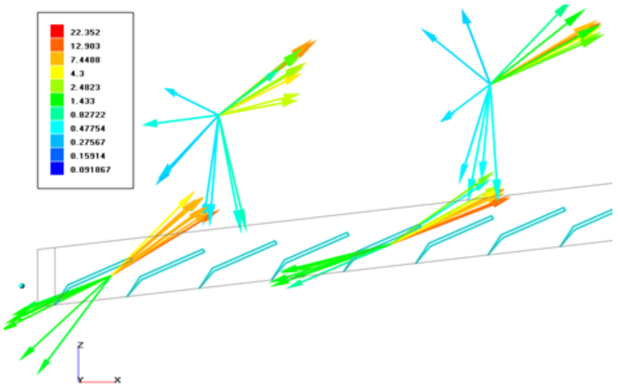

Figure 10. Distribution of the airflow velocity vectors over the front part of the scalping shoe of the combine harvester (side view)

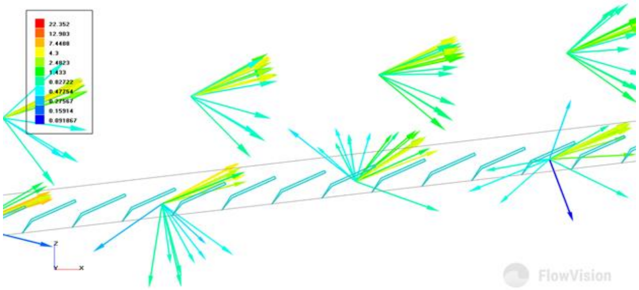

Figure 11. Distribution of the airflow velocity vectors at the outlet of the combine harvester scalping shoe (side view)

The direction and colour of the airflow velocity vectors allow concluding that the airflow will indeed swirl in the front part of the scalping shoe. The airflow velocity there is 0.3-0.7 m/s. It is seen that the vectors of the airflow velocity are directed mainly against the movement of the combine harvester (in the same direction with the sieve) and are 0.8-11 m/s. The vectors are directed in the direction of the combine harvester movement. Thus, when the sieve moves back, the sieve shoe reacts to the airflow (0.8-1.4 m/s against the main airflow).

Figures 12-14 show the calculations of the digital twin of the combine harvester cleaning system. The airflow velocity is distributed by filling over the secant longitudinal plane at a distance (12, 35, 65 cm) from the left edge of the body. The figures clearly show how the fan wheel blades distribute the airflow portions over the discharge channel and direct them into the sieves. At a distance of 12 cm from the edge (Figure 12), the airflow is uniform, and at a distance of 35 cm, the airflow is distributed unevenly. A stronger airflow enters the edge of the lower sieve, and then it enters the centre of the scalping shoe. And at a distance of 65 cm, the powerful main airflow enters the front part of the scalping shoe (Table 2).

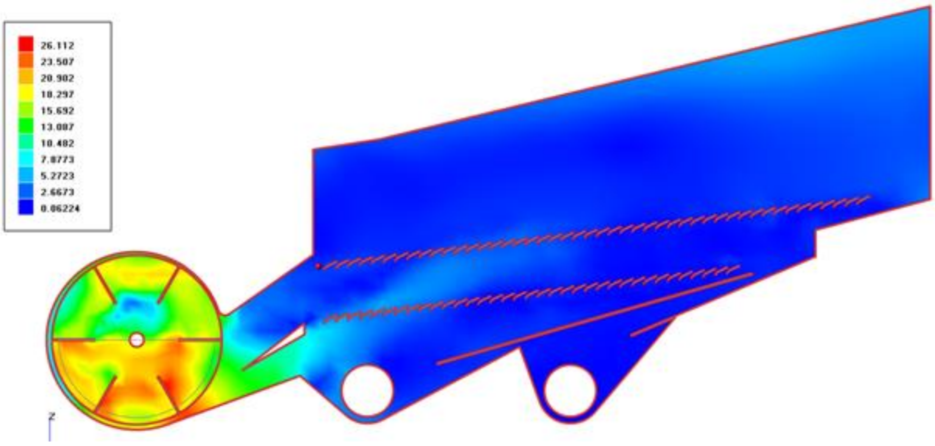

Figure 12. Calculation results: distribution of the airflow by filling over the combine harvester cleaning system (at a fan speed of 68 rad/s) (the cutting plane is at a distance of 12 cm from the left edge of the combine harvester body)

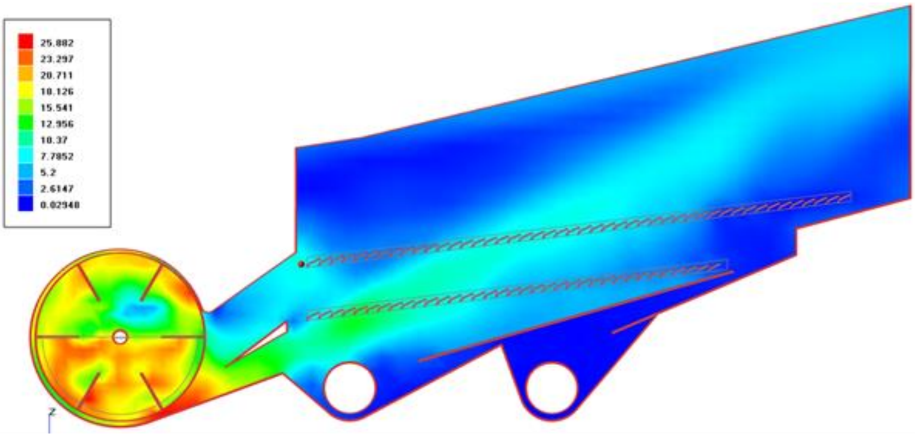

Figure 13. Calculation results: distribution of the airflow by filling over the combine harvester cleaning system (at a fan speed of 68 rad/s) (the cutting plane is at a distance of 35 cm from the left edge of the combine harvester body)

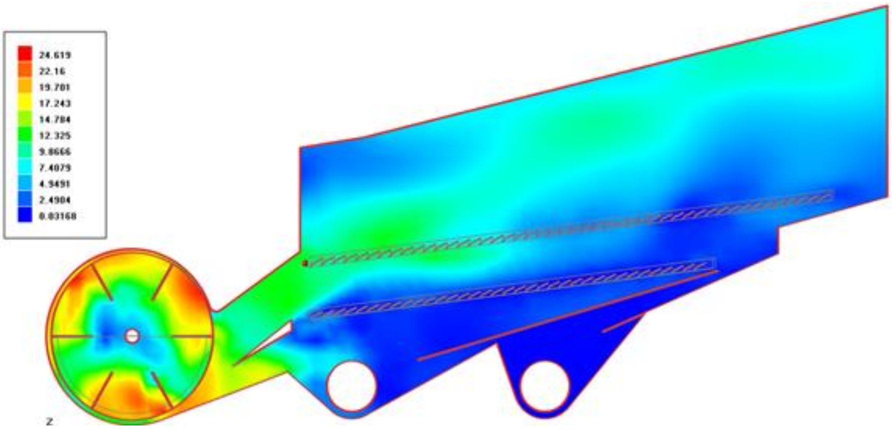

Figure 14. Calculation results: distribution of the airflow by filling over the combine harvester cleaning system (at a fan speed of 68 rad/s) (the cutting plane is at a distance of 65 cm from the left edge of the combine harvester body)

Table 2. Statistical analysis of the airflow velocity distribution over the surface of the scalping shoe of the combine harvester along the length

Parameter	Minimal	Maximal	The average value, X	Dispersion, σ^2	Squared error distance, σ	Variation, v
Velocity, m/s	3.75	10.29	6.87	3.75	1.94	28.20

Table 3. Statistical analysis of the change in the airflow velocity along the width of the New Holland TX-65 combine harvester sieves

Sieve width	**Measurement points**				
	1	**2**	**3**	**4**	**5**
Average values, m/s	1.19	1.41	1.23	1.47	1.20
Dispersion	0.08	0.20	0.69	0.35	0.28
Mean-square deviation	0.28	0.45	0.83	0.59	0.53
Variation, %	**23.12**	**31.84**	**67.51**	**40.00**	**44.10**

The statistical data of the airflow velocity distribution (coefficient of variation) over the scalping shoe width and length were determined experimentally in production conditions for combine harvesters (Acros, John Deere, Case, New Holland) (Figures 15 and 16). The airflow velocity was measured using a *KIMO* digital anemometer.

Figures 15 and 16 show that the airflow is distributed unevenly over the entire area of the sieve. It is more evenly distributed only at the beginning and at the end of the sieve. A wide scatter is observed in the middle part of the sieve shoe. Due to the wide scatter of the airflow velocity in this area, the technological process of air-type sieve cleaning of the grain heap may be disrupted. Thus, light impurities can get into the purified grain material. The situation is different along the width of the sieve shoe. In the middle part of the sieve, the airflow is more uniform, but at the sieve edges, this uniformity is disturbed.

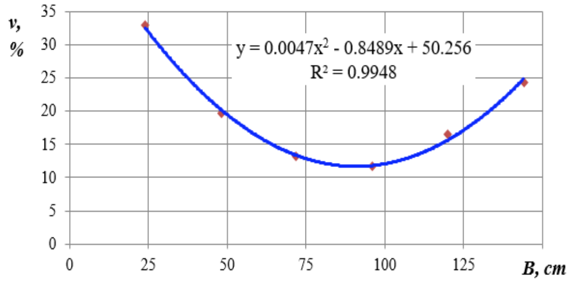

Figure 15. Distribution of the variation coefficient of variation **v** of the airflow velocity over the width **B** of the combine harvester sieve surface

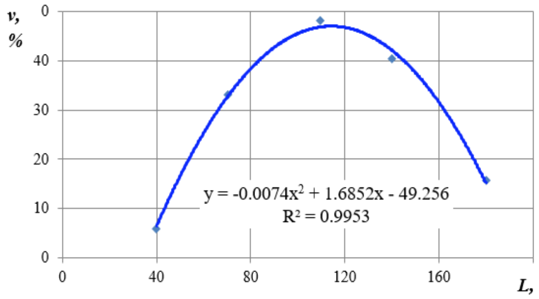

Figure 16. Distribution of the variation coefficient **v** of the airflow velocity along the length L of the combine harvester sieve surface

Table 3 shows the statistical data analysis on the measurement of airflow velocity on the sieves of the New Holland TX-65 combine harvester.

According to the variation values (Table 3), it can be said that the New Holland TX-65 combine harvester has an airflow distribution over the width of the sieve shoe that varies from 23 to 67%.

4. DISCUSSION

The experimental data on the distribution of the airflow velocity over the entire area of the sieve of the existing modern combine harvesters show that the airflow is distributed unevenly over the sieve area and varies widely. The results of other researchers prove the same [2, 5-19, 22]. Hence, the technological process of pneumatic-sieve cleaning in combine harvesters runs in violation of agrotechnical requirements [1, 12, 16, 20]. Due to the increase in performance [6, 10, 12] and throughput [6, 9, 16], there are problems with the quality of the cleaning system. This can be explained by the complexity of simultaneous control of several designs and technological parameters (fan speed and airflow velocity, sieve gaps and the angular velocity of the sieve drive crank) [13, 20] and depends on the harvested crop, its physical and mechanical properties (geometric parameters, humidity, clogging) [3, 14, 16, 17, 21, 24, 25].

The experimental data were confirmed by theoretical studies [5, 6, 22] of the mathematical description and modelling in the form of a polydisperse two-phase flow, taking into account the concentration, inertia, relaxation time, and resistance coefficient [18]. Other scientists made similar studies. Thus, Christian Korn and Thomas Herlitzius [12, 13] studied the possibility of using the associated CFD-DEM approach to simulate the process of separating grain from impurities in the cleaning device of a combine harvester.

A comparative analysis of theoretical and experimental studies showed that the reliability is more than 0.95 according to the Student's t-test, which gives reason to accept results as reliable.

Having simulated and calculated the model of a real combine harvester [2, 4-7, 11-13, 15, 19, 22] using this method, the problems of the cleaning system were identified. These problems can be solved by changing the design parameters and adding deflectors to the fan discharge channel (patent RU 2621026 C1 and RUS 175203), contributing to a more uniform airflow distribution over the channel width and the entire area of the combine harvester sieve.

The obtained characteristics help develop recommendations for optimizing the design and technical parameters of the fan and the cleaning system of the combine harvester as a whole. This modelling method makes it possible to improve the cleaning systems of combine harvesters without high costs and efforts [6].

5. CONCLUSIONS

The airflow velocities at the outlet of the radial fan discharge channel of the combine harvester cleaning system were determined at different fan wheel rotation frequencies (450-1050 min^{-1}) based on the development and research of a digital double. Experimental measurements of the airflow velocity distribution over the working part of the sieve shoe for existing cleaning system designs of modern combine harvesters were 3.75-10.2 m/s, which are implemented in a mathematical model of a complete description of the technological process of the combine harvester cleaning system functioning using the mechanic's methods of two-phase flow. The obtained parameters allow the use of the two-phase flow methods 'gas–particle' to simulate the technological process of the combine harvester cleaning system.

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NOMENCLATURE

CH	combine harvester