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Determination of Optimal Technological Parameters for Sorting Wheat Grains in Chambers of Different Constructions

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Abstract: In order to extend grain's storage time and ensure its quality, it is necessary to sort and clean it. The aim of this study was to justify the rational shape of the sorting chamber and the optimal technological parameters for the sorting of wheat grains in airflow. This study used newly designed grain sorting chambers with constant, widening, and narrowing cross-sections for the airflow sorting of "Skagen" wheat grain. The aerodynamic properties of wheat grains were investigated when moisture was at 14 ± 2.0%. The grain flow rate in the chambers varied from 4 to 12 kg min^{-1} every 2 kg min^{-1}. In addition, the airflow velocity varied from 8 to 12 m s^{-1} every 1 m s^{-1}. The tilt angle of the constant cross-section camera was increased to 5°. Experimental studies have determined a terminal airflow velocity of 11.53 m s^{-1} for wheat grains. At the terminal airflow velocity, the grain flight coefficient was obtained to be about 0.074. These studies showed that the narrowing chamber is preferable for lower grain flow rates compared to the constant cross-section of the chamber. The widening chamber requires a lower airflow velocity to achieve the same performance and quality as the other chambers.

Keywords: wheat grain; sorting; airflow velocity; flow rate; shape of the chamber

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1. Introduction

Grain sorting and cleaning is an important process for extending grain storage time and ensuring its quality. Grain cleaning separates good grain from impurities, reduces the risk of disease, and minimizes losses during processing and storage [1], thus creating a more sustainable value-added chain.

With the development of grain cleaning and sorting technologies, grain is separated, cleaned, and sorted using modern machines such as centrifugal separators, pneumatic tables, and aerodynamic separators. Methods of seed sorting are constantly being improved by finding new separation features and designing new equipment [2,3].

Pneumatic separation is one of the methods for cleaning seed mixtures [4]. The separation of grain mixtures and their components in an aspiration separator, considering their aerodynamic properties, is the most promising method from the point of view of quality improvement and production intensification. In addition, grain cleaning requires less energy [5–7]. The use of cleaning and sorting machines to clean and separate the grains into individual fractions improves the quality of the seed, and the grains in the fractions have the same physical–mechanical properties [8]. The grain cleaned and sorted by the airflow is not damaged, resulting in lower losses from cleaning [9]. Depending on the operating parameters of the machine and the properties of the grain flow factor, as well as the aerodynamic properties, the quality of sorting may vary [10]. Each particle's terminal velocity and allocation are related to the particle's size, density, shape, and surface properties [4,9,11,12]. It was found that, under sustained exposure to airflow, grains position themselves in the airflow in such a way that their aerodynamic resistance is the lowest [13].

Studies have shown that seeds with higher terminal velocities have the best biological properties, so it is recommended to use airflow to separate seeds into several fractions [14]. Krishna Prasad Shrestha designed and tested a rice cleaning and sorting machine with a can cascade in the cleaning and sorting chamber, which allowed for the increased separation of impurities from the grain [15]. Grain is better fractionated in the air stream when it is supplied into the airflow continuously and distributed evenly in the sorting chamber [16]. A cone-shaped grain flow diffuser installed in the grain cleaning chamber allows for an increase in the efficiency of the pneumatic separator by 1.6 compared to the efficiency of the conventional grain flow [17]. Pneumatic grain cleaners and sorters are popular due to their high efficiency, versatility, simple design and operation, and low operating costs, and are therefore also used by smaller grain producers [4,14,15]

As the airflow velocity increases, the friction between the air and the walls of the duct increases, resulting in higher air pressure. The amount of grain supplied into the airflow also increases the airflow pressure and, as a result, the energy consumption for grain transport [18].

The physical and mechanical grain properties play an important role in the design of cleaning machines [19]. To intensify the cleaning of grains and oilseed crops (flax, sunflower, mustard, saffron, rapeseed, soybean), it has been proposed that we study their physical and mechanical properties [20]. The accuracy of the particle separation in the airflow depends on their aerodynamic resistance, which is closely related to the surface shape of the seeds and grains and their characteristics (e.g., smooth, rough, or hair-covered surface, etc.) [21]. Studies have shown that even for the same type of seed the terminal velocity values vary quite significantly. The larger the differences between the terminal velocity values of specific particles, the easier and more effective it is to distinguish them [4].

The performance of pneumatic grain sorting chambers can be improved by incorporating mechanical elements that not only optimize the dispersion of the grain in the chamber but also create vortices in the airflow. Adamchuk et al. [22] have installed a centrifugal grain spreader in a 0.6 m diameter grain sorting chamber. With theoretical and experimental studies, the authors have shown that the use of such a pneumatic vortex chamber can increase the efficiency of pneumatic separation by 15–20%. Saitov et al. [23] developed a mathematical model for the separation of light impurities from grain in an experimental suction duct of the fan. The results of the theoretical and experimental studies differed by about 10%. It was found that the intensity of the airflow as well as the method and velocity of seed mixture delivery in the separator working zone have the greatest influence on the separation of mixture components [24].

The authors state that the angle of inclination of the airflow into the sorting chamber has little influence on the dispersion of the flow in the chamber but has a significant influence on the movement of particles and the separation effect. The grain flow and the airflow velocity do not show a clear trend in the variation of airflow dispersion. [25] The quality of seed separation in this module depends on the uniformity and degree of stability of the airflow velocity in the field working area of the sorting chamber [24].

In pneumatic grain sorters, the sorting efficiency depends on the height of the rectangular chamber. It has been observed that the efficiency increases with increasing chamber height, but only up to a certain size, after which the sorting efficiency decreases. This is because the unevenness of the airflow velocity distribution increases as the chamber height increases [26,27].

The installation of narrowing partitions in pneumatic vertical ducts allows for an increase in cleaning performance and efficiency. With an optimum width-to-length ratio of the partitions in the ducts from 0 to 5, the number of impurities that are difficult to separate from the seed can be increased by at least 20% [28]. Studies have shown that, to ensure the performance of a pneumatic grain separator, the angle of expansion of the grain sorting chamber at the point of entry into the chamber must be less than 12° [29]. In our previous research, insufficient attention has been paid to the influence of the shape of the sorting chamber on the dispersion of the chamber. Therefore, this paper presents new experimental results on the influences of a constant cross-section, widening, and narrowing grain sorting chamber on the airflow sorting of wheat "Skagen" grains.

The following research hypothesis is raised: after optimizing the shape of the sorting chamber and the technological sorting parameters of the airflow, it is possible to sort about 75% of the wheat grains at the beginning of the sorting chamber without using additional devices that intensify grain dispersion.

2. Materials and Methods

The research of wheat "Skagen" grain sorting quality was carried out in the laboratory of the Department of Agricultural Engineering and Safety at Vytautas Magnus University Agriculture Academy. The average moisture content of wheat grains was 14 ± 2.0%.

2.1. Determination of Aerodynamic Properties of Wheat Grains

The aerodynamic properties of wheat grains were determined using a classifier (Figure 1) [30]. The grain (300 g) is poured into the tank (14). The airflow velocity control damper (3) is slightly raised by the auger (4). When the fan is switched on, the fan impeller (7) is allowed to rotate freely for about 30 s to stabilize the airflow velocity in the suction duct (11). A gap of approximately 3 mm shall be left between the bottom of the grain tank (14) and the valve (13) to allow the bottom to vibrate and the grain to flow out of the tank in a continuous stream. When it is observed that only very fine impurities are sucked into the settling tank (10) (box 19), the airflow velocity (lower limit) in the suction duct is measured with the airflow velocity measuring device "DO 9847" (16). After all the grain has been discharged from the tank, the damper (3) is closed and the grain from boxes 18 and 19 is poured in. The damper (3) is then lifted using an auger (4) so that all the grain is sucked into the settling tank (10). A few of the coarsest grains may fall into the box (18). The airflow velocity is measured in the suction duct (upper limit). The airflow velocity range between the minimum and maximum values is divided into eight equal parts (classes) and the average airflow velocity is calculated. The grain is again poured into the tank (14). The fan is turned on. The airflow velocity control damper (3) is raised by the auger (4) so that the airflow velocity in the suction duct corresponds to the lower limit. The valve (13) is opened. All grains are allowed to fall out of the tank (14). The valve (13) is closed again. The grain from one box (18) is poured into the grain tank, and the grain from the other box (19) is poured out and weighed. Then, the airflow regulating damper (3) is raised by the auger (4) so that the airflow velocity in the suction duct increases to the value of the next velocity class. This test is performed three times.

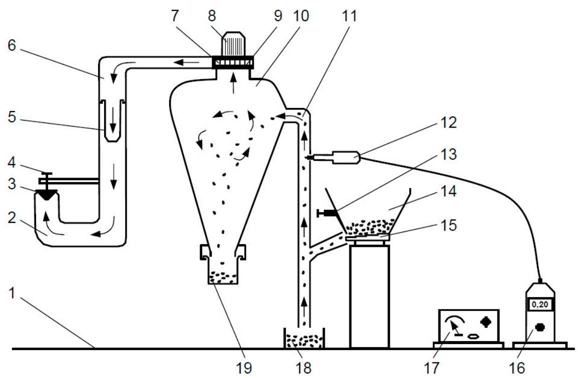

Figure 1. Scheme of the classifier: 1—rack, 2—duct, 3—airflow control damper, 4—auger, 5—filter, 6—air cleaning chamber, 7—fan impeller, 8—electric motor, 9—sieve, 10—settling tank, 11—suction duct, 12—airflow velocity measuring sensor, 13—valve, 14—grain tank, 15—tank bottom vibrator, 16—airflow velocity measuring device "DO 9847", 17—control panel, 18 and 19—grain boxes.

After the measurements have been made, the average grain flight coefficient for each class is calculated [31]:

$$k_f = \frac{g}{v_{n\ class}^2} \quad (1)$$

where g is the acceleration of gravity, in ms^{-2}, and $v_{n\ class}^2$ is the terminal velocity of a grain of a specific class, in ms^{-2}.

The average terminal velocity of all classes of grain is calculated [31]:

$$v_{cr} = \frac{\sum v_{n\ class} \cdot m_n}{\sum m_n} \quad (2)$$

where m_n is the grain mass of a class, in g.

2.2. Determination of Wheat Grain Flow in Sorting Chambers of Different Cross-Sections

The laboratory studies on wheat grain sorting were carried out at the grain sorting stand (Figure 2).

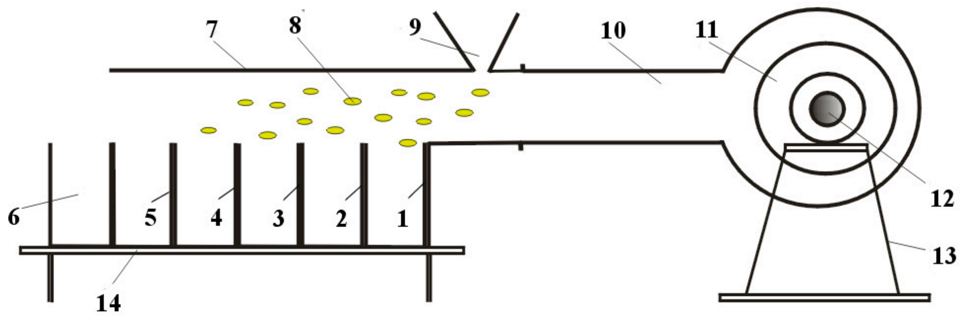

Figure 2. Scheme of the wheat grain sorting stand: 1–6—collecting boxes, 7—grain sorting chamber, 8—grain, 9—grain tank, 10—airflow velocity equalization tank, 11—fan, 12—electric motor, 13 and 14—racks.

The grain sorting stand used three types of sorting chambers: a constant cross-section (Figure 3a), a widening cross-section (Figure 3b), and a narrowing cross-section (Figure 3c). The dimensions of the chamber with a constant cross-section were the same as those of airflow velocity equalization tank 10 (Figure 2): height—170 mm, width—170 mm, length—1250 mm. The height of the narrowing cross-section chamber decreases continuously from 170 to 70 mm, while that of the widening cross-section chamber increases from 170 to 270 mm. In each chamber, 15 mm diameter holes were drilled at 150 mm intervals in the center of each box for the insertion of the airflow velocity sensor and the measurement of airflow velocity. The airflow velocity measurement points are shown in Figure 3.

The airflow velocity in the sorting chambers varied from 8 to 12 m s^{-1} every 1 m s^{-1}, and the grain flow rate varied from 4 to 12 kg min^{-1} every 2 kg min^{-1}. In addition, the positioned angle of the constant cross-section sorting chamber was increased by 5°. The airflow velocity was changed by changing the speed of the electric motor with a frequency converter “Delta VFD-B” in the fan impeller drive motor. The airflow velocities at different points in the chamber were measured with a multifunction data logger “DO 9847” with a measurement range of 0.1 to 40 m s^{-1}.

The grains were weighed and the dispersion of the grains in the sorting chamber was calculated. A weighing scale “CAS SW-1” was used to weigh the grains in the boxes, with a measuring range of up to 5 kg and an error of 2 g.

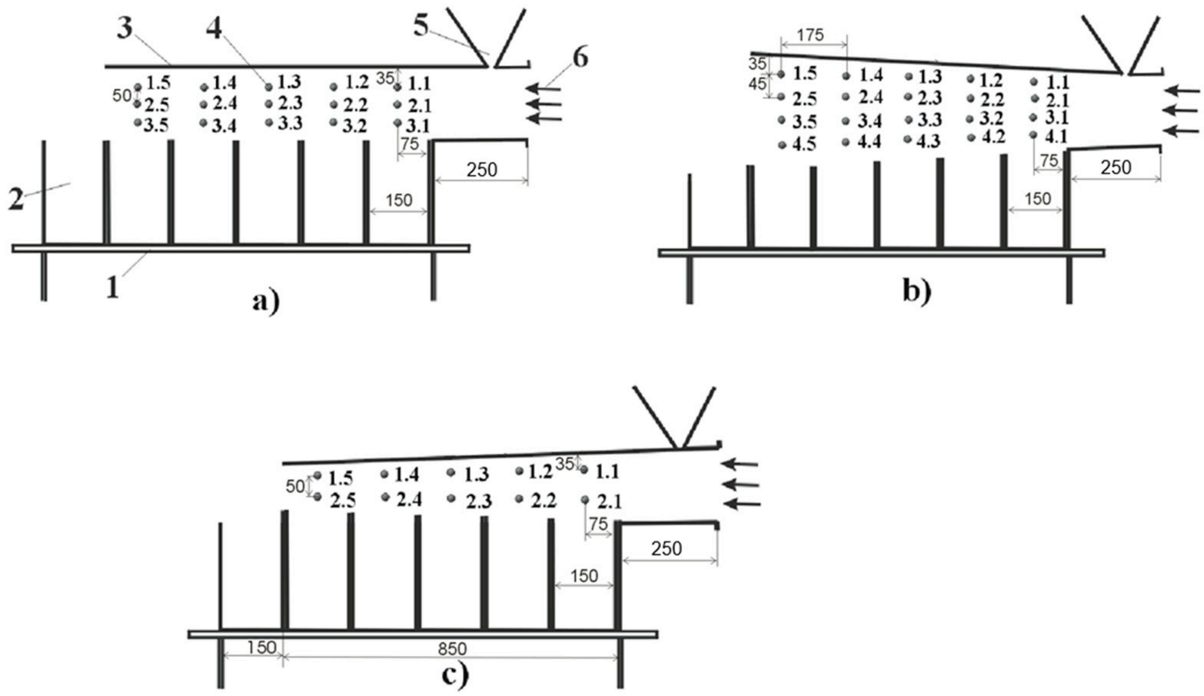

Figure 3. Grain sorting chambers: (**a**) constant cross-section, (**b**) widening cross-section, (**c**) narrowing cross-section, 1—rack, 2—boxes, 3—upper part of the sorting chamber, 4—the airflow velocity measurement points, 5—grain tank, 6—direction of the airflow.

2.3. Statistical Analysis

Data obtained for the research were analyzed using a one-way analysis of variance (ANOVA) module with the statistical software Statistica 10.0 to compare the means of the parameters obtained. A significance level of 0.05 was used as the criterion for tests of significance throughout the data analysis. The least significant difference R0.05 (posthoc test LSD) was calculated at the confidence level of 95% [32].

3. Results

3.1. Aerodynamic Properties of Wheat Grains

The quality of grain sorting is determined by the aerodynamic properties of the grain [9,33–35] and the terminal velocity of the particles used in the pneumatic separation process [16]. Therefore, this experimental research aims to determine the influence of the vertical airflow velocity on the quantitative dispersion of grain mass parts, and grain flight of wheat grain. In addition, based on the obtained experimental results, the terminal velocity is calculated. The studies showed that the highest proportion of grains sucked was obtained in the sixth (31.22%) and seventh (24.78%) classes at average airflow velocities of 12.1 m s^{-1} and 13.1 m s^{-1}, respectively (Figure 4). No significant difference was found between these variants. The lowest proportion of grains sucked was found in the first (3.33%), second (5.89%), third (5.33%), and eighth (4%) classes, with the average airflow velocities of 7.8 m s^{-1}, 8.1 m s^{-1}, 9.1 m s^{-1}, and 14.1 m s^{-1}, respectively. No significant difference was found between these variants. According to the results of the average airflow velocity and the grains sucked, a terminal airflow velocity of 11.53 m s^{-1} was calculated. In the grain sorting process, the terminal airflow velocity of the grain must be used as a guide for determining the fan airflow rate [6,33,36].

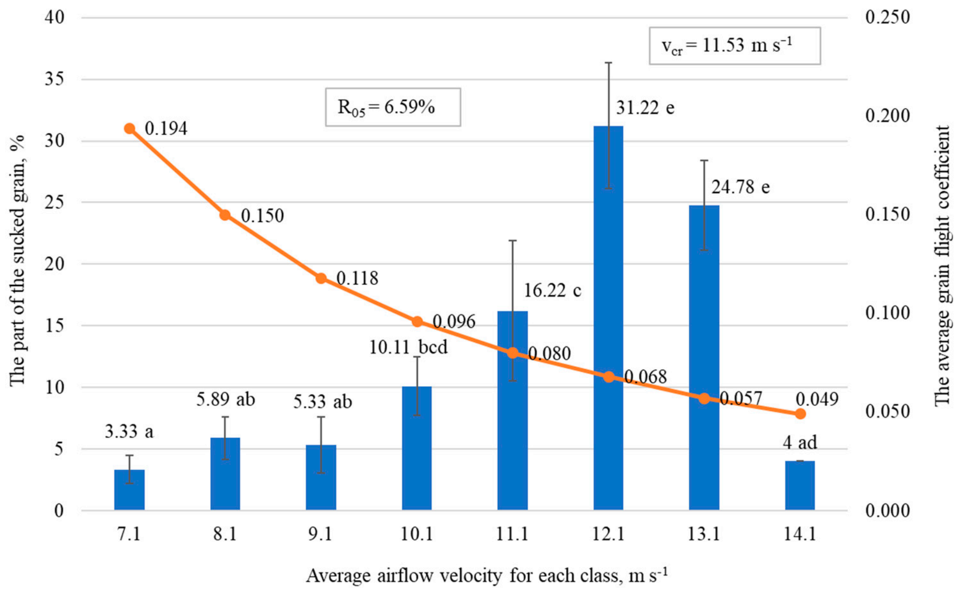

Figure 4. The influence of the vertical airflow velocity on the quantitative dispersion of grain mass part and grain flight coefficient. Error bars represent the 95% standard error. Matching letters indicate no significant difference between the average airflow velocity.

Experimental studies showed a decrease in the grain flight coefficient (74.74%) with an increase in the average airflow velocity from 7.1 m s^{-1} to 14.1 m s^{-1} (Figure 4). As the average airflow velocity increased from 7.1 m s^{-1} to 14.1 m s^{-1} every 1 m s^{-1}, a decrease in the grain flight coefficient was observed, with decreases of 22.68%, 21.33%, 18.64%, 16.67%, 15%, 16.18%, and 14.04%, respectively. The study showed that at the average airflow velocity higher than 11.53 m s^{-1} and grain flight coefficient lower than 0.074, the grain will be carried away with light impurities in the grain sorting process. This will happen due to the grain's inability to resist the airflow [14].

3.2. Wheat Grain Flow in Sorting Chambers of Different Cross-Sections

Seed sorting is strongly influenced by airflow velocity [33,34]. Therefore, these studies evaluated the dispersion of the airflow velocities in the different grain sorting chambers when the airflow velocity at the beginning of the sorting chamber was 10 m s^{-1} (Table 1). It was found that in the narrowing chamber, the airflow velocity was similar (about 10 m s^{-1}) to the one at the beginning of the chamber, while it decreased in the constant cross-section and the widening chamber. In the constant cross-section chamber, a more significant decrease in airflow velocity (from 10 m s^{-1} to 8.6 m s^{-1}) was observed in the upper part of the chamber, while in the widening cross-section chamber, a significant decrease was observed in the upper part of the chamber (from 8.8 m s^{-1} to 7.5 m s^{-1}) as well as in the lower part of the chamber (from 9.9 m s^{-1} to 7.3 m s^{-1}). The increasing cross-section of the widening sorting chamber had the greatest influence on the more significant decrease in airflow velocity compared to the constant cross-section sorting chamber. By increasing the chamber height, the unevenness of the airflow velocity distribution increases [26,27]. The results of the airflow velocity dispersion in the different sorting chambers suggest that, at the beginning of the sorting chamber, a sorting chamber with a narrowing cross-section would be best suited for the separation of the large grains, as the airflow velocity in the length of the sorting chamber was the highest. Other authors claim that there is an increase in grain cleaning performance and efficiency when narrowing partitions are installed in pneumatic vertical ducts [28].

Table 1. Dispersion of airflow velocities in the different grain sorting chambers with an airflow velocity of 10 m s^{-1} at the start of the sorting chamber.

Measurement of Airflow Velocity in a Grain Sorting Chamber of Constant Cross-Section					
Measurement points	1.1	1.2	1.3	1.4	1.5
Airflow velocity, m s^{-1}	10	10	9.8	8.9	8.6
Measurement points	2.1	2.2	2.3	2.4	2.5
Airflow velocity, m s^{-1}	10	9.9	9.8	9.7	9.5
Measurement points	3.1	3.2	3.3	3.4	3.5
Airflow velocity, m s^{-1}	10	9.7	9.7	9.5	9.4
Measurement of Airflow Velocity in a Grain Sorting Chamber of Widening Cross-Section					
Measurement points	1.1	1.2	1.3	1.4	1.5
Airflow velocity, m s^{-1}	8.8	8	7.9	7.7	7.5
Measurement points	2.1	2.2	2.3	2.4	2.5
Airflow velocity, m s^{-1}	9.9	9.4	8.9	8.3	7.8
Measurement points	3.1	3.2	3.3	3.4	3.5
Airflow velocity, m s^{-1}	10	9.9	9.6	8.8	7.7
Measurement points	4.1	4.2	4.3	4.4	4.5
Airflow velocity, m s^{-1}	9.9	8.9	8.4	7.7	7.3
Measurement of Airflow Velocity in a Grain Sorting Chamber of Narrowing Cross-Section					
Measurement points	1.1	1.2	1.3	1.4	1.5
Airflow velocity, m s^{-1}	10.2	10.3	10.3	10.2	10.3
Measurement points	2.1	2.2	2.3	2.4	2.5
Airflow velocity, m s^{-1}	10	9.9	10.2	-	-

During experimental studies of grain sorting in different chambers (constant cross-section, widening, and narrowing), when the supplied grain flow rate varies from 4 to 12 kg min^{-1} every 2 kg min^{-1}, at a constant airflow velocity (10 m s^{-1}), a similar tendency of the dispersion of the grain was found in all chambers (Figure 5). In different sorting chambers, the first boxes had the highest percentages of grain compared to the other four boxes, and the percentage of grain increased with increasing grain flow rate. In the second, third, fourth, and fifth boxes, the percentage of grain decreased and was significantly lower compared to the first boxes. During the study, it was observed that at high grain concentrations in the airflow, the frequent contact of the grains with other grains moving in the airflow reduced the sorting quality of the grains, resulting in significantly different percentages of grains in the first boxes. The experimental results allow us to argue that the narrowing chamber is suitable for sorting smaller grain flows, compared to a constant cross-section and a widening chamber with the same airflow velocity at the beginning of the chamber. These studies show that the widening chamber can be operated at a lower airflow velocity to achieve the same performance and grain sorting quality as the other chambers studied. Previous studies have shown that the height of the sorting chamber positively influences the airflow sorting of grains [29]. The widening chamber can be fed with about 8–10 kg min^{-1} of grain at a 10 m s^{-1} airflow velocity.

Research has shown that while supplying a grain flow rate of 6 kg min^{-1} into a constant cross-section chamber, when the airflow velocity changes from 8 m s^{-1} to 12 m s^{-1} every 1 m s^{-1}, the percentage of grain in the first box decreases as the airflow velocity increases and increases in the other four boxes (Figure 6). The first box has the highest percentage of grain compared to the other four boxes up to an airflow velocity of 11 m s^{-1}. However, at 12 m s^{-1}, the percentage of grain in the first box becomes similar to that in the second box, but still higher than that in the third, fourth, and fifth boxes. At an airflow velocity of 10 m s^{-1}, no more than 6 kg min^{-1} of grain should be fed into a constant cross-section chamber, as the grains moving in the airflow of the sorting chamber increase the air pressure and the resistance to airflow [18]. We do not provide the results for the narrowing and the widening chambers because studies have shown that the narrowing chamber is more prone to clogging at grain flow rates of 6 kg min^{-1}, 8 m s^{-1}, and 9 m s^{-1}. This may be explained by the fact that the gaps between the grains are greatly reduced, and the large grains create a resistance for the small ones to penetrate through the grains [37]. Therefore, a lower grain flow rate is recommended at these airflow velocities. In the widening chamber, the trend of the results is similar to that of the constant cross-section chamber, but only from the airflow velocity of 9 m s^{-1}, because 8 m s^{-1} is too low for grain sorting and the grains are not blown.

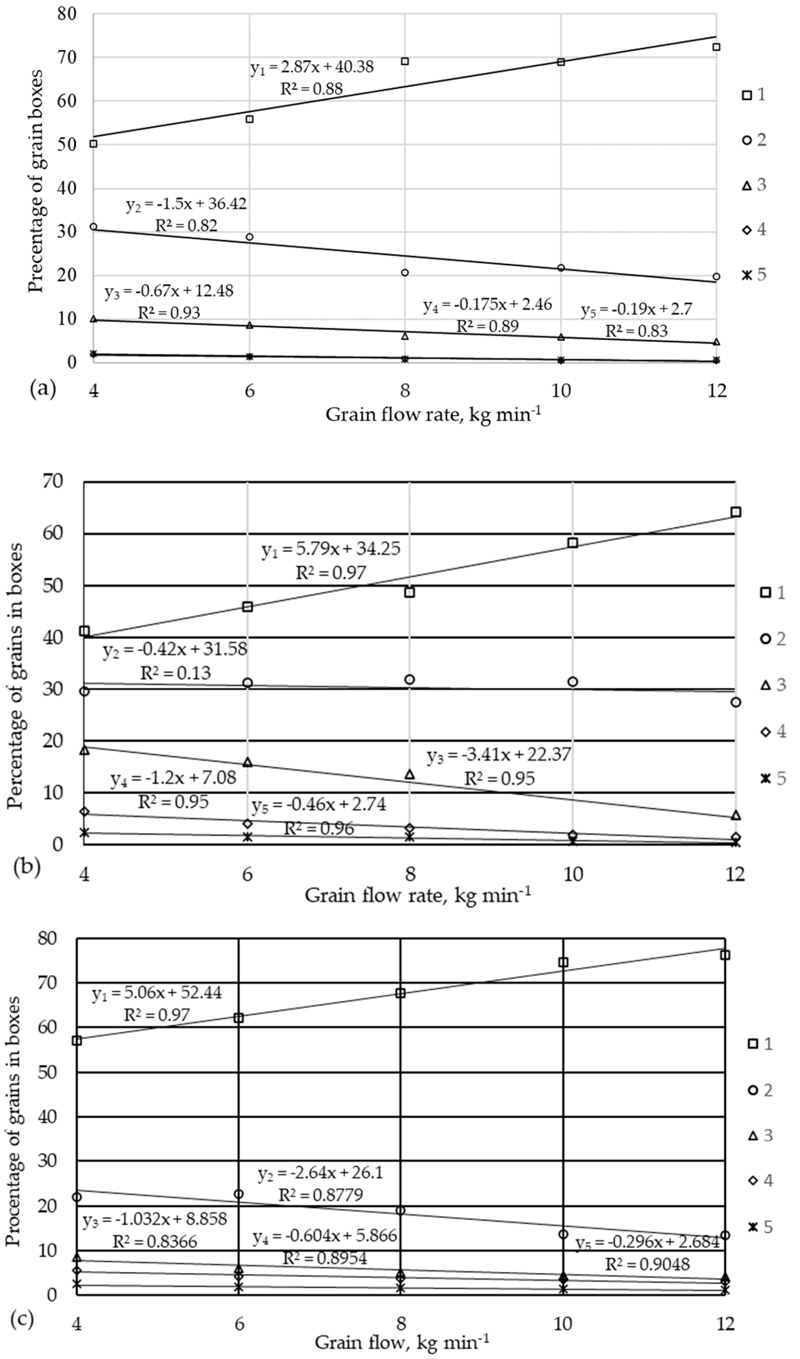

Figure 5. The influence of the grain flow rate on grain dispersion in a constant cross-section chamber (**a**), widening chamber (**b**), and narrowing chamber (**c**), with the airflow velocity of 10 ms^{-1}: 1—1st box; 2—2nd box; 3—3rd box 3; 4—4th box; 5—5th box.

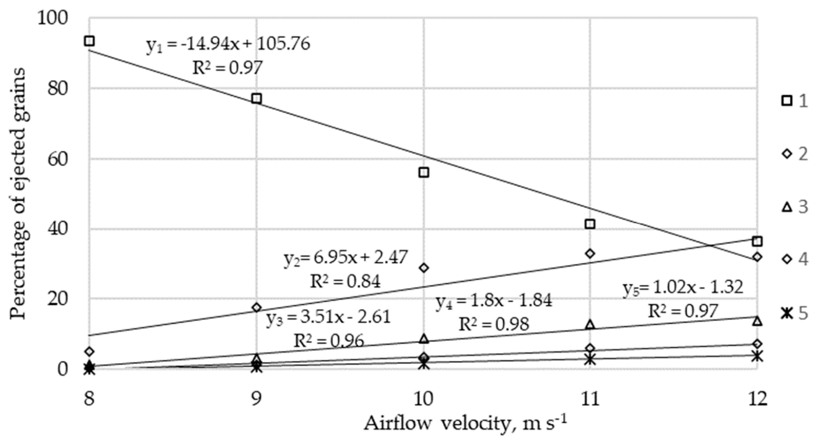

Figure 6. The influence of the airflow velocity on grain dispersion in the constant cross-section chamber with the grain flow rate of 6 kg min^{-1}: 1—1st box; 2—2nd box; 3—3rd box; 4—4th box; 5—5th box.

Comparing the work process of the sorting chambers of different shapes (constant cross-section, narrowing, and widening) with each other, at the airflow velocity of 11 m s^{-1} and grain flow rate of 10 kg min^{-1}, the highest (74.5%) percentage of grain was determined in the first box of the narrowing chamber. It is 30.07% more than the first box of the constant cross-section chamber and 41.88% more than that of the widening chamber (Figure 7). However, in the second box of the narrowing chamber, the number of grains was the lowest compared to those of the constant cross-section and the widening chambers, i.e., 53.58% and 68.59% fewer grains, respectively. The grain is best distributed in the chamber with a constant cross-section: the first box holds most of the grain, i.e., 52.1%, the second box—29.3%, the third box—10.1%, the fourth box—4.9%, and about 2.2% of the small grains and light impurities are ejected from the chamber into the fifth and sixth boxes. In the narrowing chamber, however, almost all the grains are fed into the first box, varying in size and aerodynamic properties. In the case of the widening chamber, the grain dispersion parameters are like those of the constant cross-section chamber, but grain sorting is insufficient.

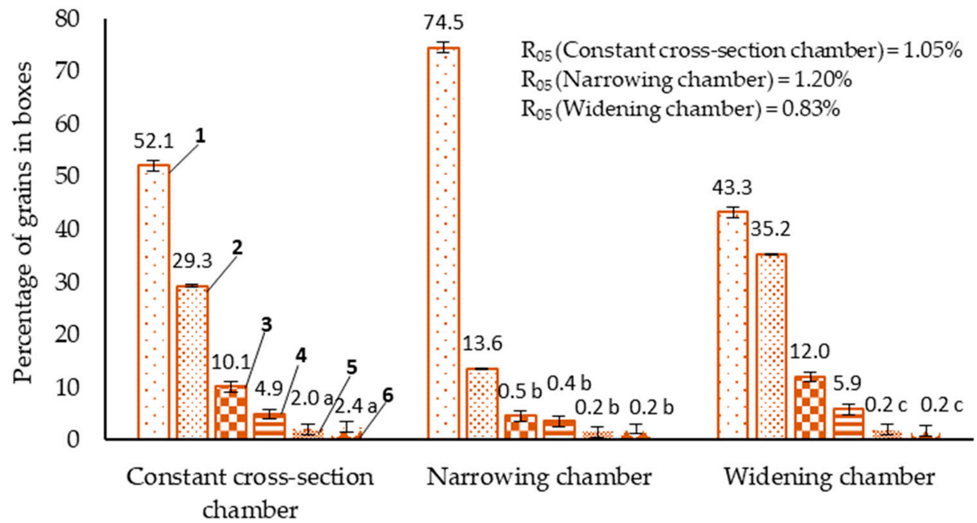

Figure 7. The influence of different chamber shapes on grain dispersion at the airflow velocity of 11 m s^{-1} and grain flow rate of 10 kg min^{-1}: 1—1st box; 2—2nd box; 3—3rd box; 4—4th box; 5—5th box; 6—6th box. Error bars represent the 95% standard error. Matching letters indicate no significant difference between chamber shapes.

A review of the results of this study reveals trends that describe the characteristics of the chambers to achieve similar grain dispersions. It is recommended to select a higher airflow velocity and reduce the grain flow rate when using a narrowing chamber, which will give the grain more room to move and be more dispersed, affecting its extremity and dispersion. This chamber should also be used for smaller grain flow rates. The installation of narrowing partitions in pneumatic channels with vertical airflow allows for the increased productivity and efficiency of seed cleaning. The narrowing chamber should be fed with about 4 kg min^{-1} of grain at an airflow velocity of 11 m s^{-1}. Studies have shown that the installation of narrowing partitions in pneumatic ducts with a vertically rising airflow allows for an increase in the productivity and efficiency of seed cleaning [38], and a similar trend has been observed in the narrowing horizontal grain sorting chamber.

The widening chamber can be fed at a lower airflow velocity and the grain flow rate can be slightly higher. This chamber shape allows the grain to move more easily in the longitudinal direction of the chamber, which improves the dispersion of the grain in the air stream. The recommended parameters to achieve the best grain dispersion are the following: grain flow rate of 8–10 kg min^{-1} and airflow velocity of 10 m s^{-1}.

This research of these chambers suggests that the shape of the constant cross-section chamber is intermediate between the two. This chamber achieves the highest throughput at a grain flow rate of 12 kg min^{-1} and an airflow velocity of about 12 m s^{-1}, but under these conditions, the quality of the grain decreases.

The influence of the angle of inclination of the grain sorting in a constant cross-section chamber on the dispersion of the grain along the length of the chamber was investigated. Increasing the angle of inclination of the sorting chamber to 5° significantly increased (21%) the amount of grain falling into the first box. However, the amount of grain in the subsequent boxes was significantly lower compared to the horizontal camera with the initial angle of 0° (Figure 8). It was observed that increasing the angle of inclination of the sorting chamber resulted in poorer grain sorting quality due to the higher elevation of the walls of the grain outlets. A similar trend in grain dispersion was observed in the narrowing and widening chambers.

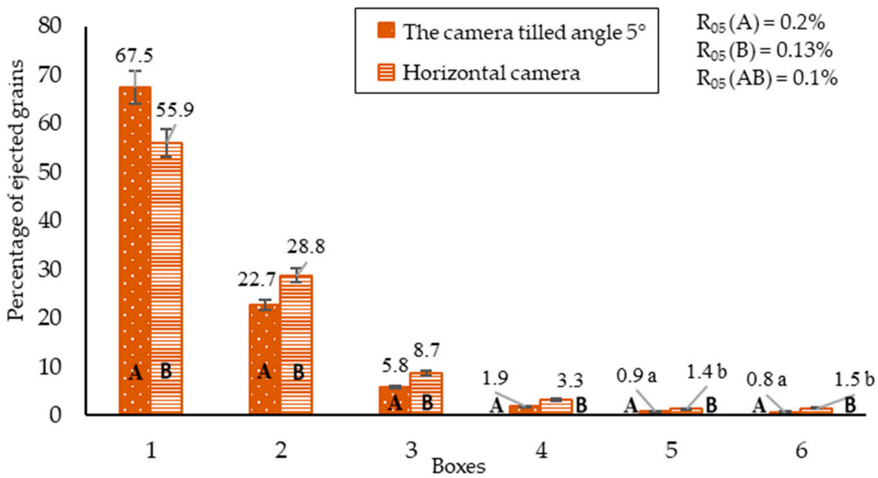

Figure 8. The influence of the tilt angle of the grain sorting chamber of the constant cross-section on grain dispersion in the chamber at the airflow rate of 10 m s^{-1} and grain flow rate of 6 kg min^{-1}. Error bars represent the 95% standard error. Matching letters indicate no significant difference between the boxes.

When cleaning and sorting grain, it is important to select the parameters of the cleaning machines so that as little grain as possible is blown outside the sorting chamber, with minimum grain loss and without compromising the quality of the sorting. Studies have shown that the flow rate of grain fed into the sorting chamber affects not only the grain discharge in the airflow but also the loss of grain blown out of the chamber (Figure 9). The trend of the grain blown out of the constant and widening cross-section sorting chambers was similar, with grain losses decreasing. At lower grain flow rates, larger gaps are created between the grains moving in the airflow, the grains are less likely to bump into each other, and the airflow carries them further away from the beginning of the sorting chamber. Increasing the grain flow rate results in the grains not being sufficiently loosened by the airflow, and the grain layer becomes more resistant to the airflow, resulting in a reduction in grain loss but a deterioration in the quality of the sorting of the grain. Increasing the airflow velocity from 8 to 12 m s^{-1} at a grain flow rate of 6 kg min^{-1} resulted in an average increase in grain loss from the chamber of between 0.8 and 5.2% (Figure 10). This study showed that above the airflow velocity of 11 m s^{-1}, the grain sorting quality deteriorates, with a greater variation in the size of grain entering the boxes at the bottom of the sorting chamber. The results showed that with the airflow velocity of 11 m s^{-1} at the beginning of the grain sorting chambers, the average weight of 1000-grain leaving the sorting chambers was 26.04 ± 1.14 g in the constant cross-section chamber and 21.87 ± 2.21 g in the widening chamber.

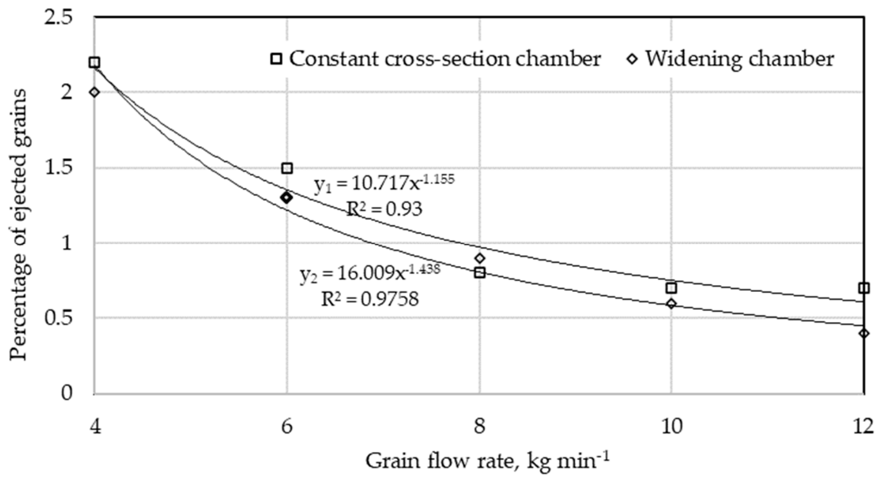

Figure 9. The influence of the grain flow rate of the grain sorting chamber on grain losses at the airflow velocity of 10 m s^{-1}.

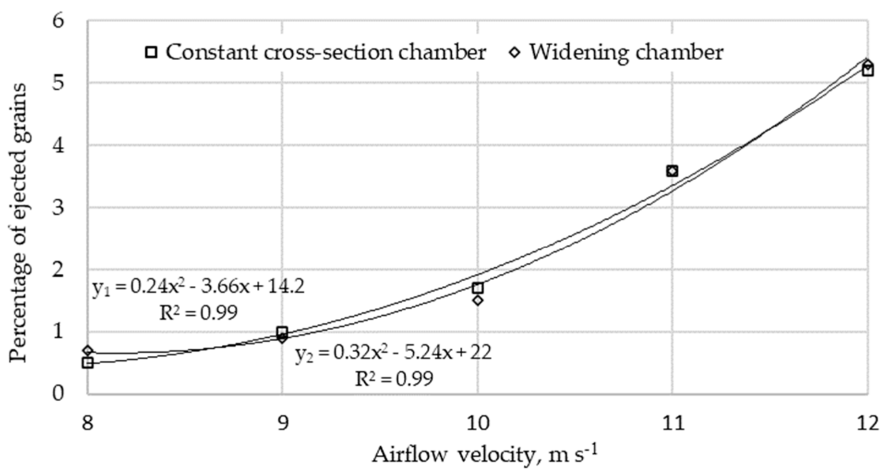

Figure 10. The influence of the airflow velocity of the grain sorting chamber on grain losses at the grain flow rate of 6 kg min^{-1}.

4. Discussion

Air flow in grain cleaning and sorting machines is often used to separate impurities from grain and to sort cleaned grain. Grain cleaning and sorting using airflow is not as high-quality as using sieve grain cleaners but has the advantage in that the grain has less contact with the working parts of the cleaning machine. As a result, the surface of the grain is less damaged mechanically, which influences further storage and processing [4,39]. The airflow rate is used to enhance the separation of grains and impurities. Particles with different aerodynamic characteristics have distinguished critical speeds, which determine their separation in the airflow [8,14]. Many studies have analyzed the cleaning and sorting of grain in airflow, but the issues of the intensification of particle separation in airflow are still relevant [4,14,15]. Usually, airflow speed differences might be observed at the beginning and the end of the sorting chamber. It depends on the shape and design of the grain cleaning and sorting chamber in which the air is circulated [11,12]. The important issue is to ensure the uniform speed of the airflow and the pressure in the cross-section of the sorting chamber. Additional means are used to ensure a uniform airflow rate, but they usually form resistance to the airflow, which causes higher grain cleaning and sorting energy costs [6,40].

This grain sorting study was performed using sorting chambers of different shapes to ensure an even distribution of airflow without using any additional means for airflow leveling.

The results of the working processes of different shape sorting chambers (cross-sectional, widening, and narrowing) show that when the airflow rate of 11 m s^{-1} and 10 kg min^{-1} was used, ~75% of the separated grain fell into the first box of the narrowing chamber. This is ~30% more than in the first box of the constant cross-section chamber and 42% more than that in the widening chamber. However, approximately 54% and 68% less grain was in the second box of the narrowing chamber compared to the grain sorting chambers of the constant and widening cross-section chambers.

The larger amount of grain entering the narrowing chamber does not ensure sufficient sorting of the grain, as their size and aerodynamic properties differ, therefore, in the narrowing sorting chamber, qualitative sorting might be ensured using a smaller grain flow.

In the constant cross-section chamber, grain is distributed evenly: the first box contains the largest percentage of the separated grain (~52%), the second box—29.3%, the third box—10.1%, and the fourth box contains 4.9% and approximately 2.2% of the fine grains and low-mass impurities from the chamber. The results obtained in this study are in line with the results of other researchers [2,8,33]. The obtained results in the widening and constant cross-section grain sorting chambers were similar.

These research results will provide knowledge to the manufacturers of grain cleaning and separation machines on how to ensure high-quality grain cleaning and sorting in pneumatic separators with different shapes and dimensions to the sorting chamber.

5. Conclusions

Experimental studies determined the terminal airflow velocity of 14% moisture content wheat grains to be 11.53 m s^{-1}. In the case of terminal airflow, the grain flight coefficient was about 0.074. After conducting grain sorting experimental studies with different grain sorting chambers (constant cross-section chamber, widening chamber, and narrowing chamber) at different airflow velocities, it was found that the area of the sorting chamber and the airflow velocity are the most important factors influencing the dispersion of grain.

At an airflow velocity of 10 m s^{-1}, about 6 kg min^{-1} of grain can be fed into the constant cross-section chamber, and about 80% of the wheat grain is then sorted qualitatively at the beginning of the sorting chamber into the first two boxes. In the widening cross-section chamber, under similar parameters, about 75% of the grain is fed into the first boxes, but the quality of the grain sorting was better due to the increasing cross-sectional area of the chamber. The narrowing cross-section area of the sorting chamber can be used for grain sorting in low-efficiency machines. Under rational grain sorting parameters (an airflow velocity of 10 m s^{-1} and a grain flow rate of 6 kg min^{-1}), the amount of small grains ejected from the constant and widening cross-section chambers is about 1.5%.

The optimization of the shape and dimensions of the grain sorting chamber enables ensuring the quality of grain sorting in the airflow without the use of additional airflow distribution means which form resistance to the airflow and increase the energy consumption. The obtained research results can be used in designing grain cleaning chambers in pneumatic grain cleaners.

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References

1. Tibola, C.S.; Fernandes, J.M.C.; Guarienti, E.M. Effect of cleaning, sorting, and milling processes in wheat mycotoxin content. *Food Control* **2016**, *60*, 174–179. [CrossRef]
2. Konopka, S.; Choszcz, D.; Wierzbicki, K. Wpływ wilgotności mieszaniny na skuteczność procesu rozdziału gryki od zanieczyszczeń w obrotowym sicie szczelinowym (The effect of the moisture content of a seed mixture on the separation efficiency of buckwheat seeds and impurities in a rotary groove separator). *Inżynieria Rol.* **2000**, *9*, 119–125.
3. Xiao, Y.; Wang, H.; Shao, X. 2D numerical modeling of grain-sorting processes and grain size distributions. *J. Hydro-Environ. Res.* **2014**, *8*, 452–458. [CrossRef]
4. Choszcz, J.; Reszczynski, P.S.; Kolankowska, E.; Konopka, S.; Lipinski, A. The Effect of Selected Factors on Separation Efficiency in a Pneumatic Conical Separator. *Sustainability* **2020**, *12*, 3051. [CrossRef]
5. Bulgakov, V.; Nikolaenko, S.; Holovach, I.; Adamchuk, V.; Kiurchev, S.; Ivanovs, S.; Olt, J. Theory of grain mixture particle motion during aspiration separation. *Agron. Res.* **2020**, *18*, 8–37. [CrossRef]
6. Bazaluk, O.; Postnikova, M.; Halko, S.; Mikhailov, E.; Kovalov, O.; Suprun, O.; Miroshnyk, O.; Nitsenko, V. Improving Energy Efficiency of Grain Cleaning Technology. *Appl. Sci.* **2022**, *12*, 5190. [CrossRef]
7. Astanakulov, K.D.; Karimov, M.R.; Khudaev, I.; Israilova, D.A.; Muradimova, F.B. The separation of light impurities of safflower seeds in the cyclone of the grain cleaning machine. *IOP Conf. Ser. Earth Environ. Sci.* **2020**, *614*, 012141. [CrossRef]
8. Vaiciukevičius, E.; Strakšas, A. Investigation of biometric parameters and aerodynamic properties of buckwheat. *Lith. Agric. Univ. Res. Pap.* **2009**, *83*, 92–97.
9. Gupta, R.K.; Arora, G.; Sharma, R. Aerodynamic properties of sunflower seed (*Helianthus annuus* L.). *J. Food Eng.* **2007**, *79*, 899–904. [CrossRef]
10. Giyevskiy, A.M.; Orobinsky, V.I.; Tarasenko, A.P.; Chernyshov, A.V.; Kurilov, D.O. Substantiation of basic scheme of grain cleaning machine for preparation of agricultural crops seeds. *IOP Conf. Ser. Mater. Sci. Eng.* **2018**, *327*, 042035. [CrossRef]
11. Mokhtari Nahal, A.; Arabhosseini, A.; Kianmehr, M.H. Separation of shelled walnut particles using pneumatic method. *Int. J. Agric. Biol. Eng.* **2013**, *6*, 88–93.
12. Srivastava, K.; Carroll, E.; Roger, G.; Rohrbach, P.; Buckmaster, R.D. *Grain Harvesting. Chapter 12 in Engineering Principles of Agricultural Machines*, 2nd ed.; Asabe: St. Joseph, MI, USA, 2006; pp. 403–435.
13. Aliev, E.B.; Shevchenko, I.A. Investigation of Aerodynamic Properties of Oilseeds. *Bull. Agrar. Sci. (Вiсник Аграрної Науки)* **2017**, *3*, 63–65.
14. Stepanenko, S. Research pneumatic gravity separation grain materials. *Mech. Agric.* **2017**, *63*, 54–56.
15. Shrestha, K.P.; Parajuli, P.; Baral, B.; Shrestha, B.P. Mathematical modeling, simulation and analysis of rice grain movement for design and fabrication of low-cost winnowing machine. *J. Mech. Eng. Res.* **2017**, *9*, 012041. [CrossRef]
16. Panasiewicz, M.; Sobczak, P.; Mazur, J.; Zawiślak, K.; Andrejko, D. The technique and analysis of the process of separation and cleaning grain materials. *J. Food Eng.* **2012**, *109*, 603–608. [CrossRef]
17. Chernyakov, A.V.; Koval, V.S.; Yatsunov, A.N.; Begunov, M.A.; Shevchenko, A.P.; Evchenko, A.V. Research of a conical pneumatic grain separator with a device for forced light fraction removal. *IOP Conf. Ser. Earth Environ. Sci.* **2021**, *659*, 012041. [CrossRef]
18. Kılıçkan, A.; Güner, M. Pneumatic Conveying Characteristics of Cotton Seeds. *Biosyst. Eng.* **2006**, *95*, 537–546. [CrossRef]
19. Kumar, S.; Singh, S.; Vishwakarma, R.K.; Singh, B.R. Evaluating the effects of some relevant parameters on physicomechanical and aerodynamic properties of sunflower seed. *New Agric.* **2019**, *30*, 1–8.
20. Aliev, E.; Pryshliak, V.; Yaropud, V. Research of physical and mechanical properties of oilseed crops. *Motrol. Comm. Mot. Energetics Agric.* **2017**, *19*, 103–108.
21. Qing, T.; Chongyou, W.; Suzhen, W.; Chengwen, Z.; Yongfei, S. Research advances and prospects in cleaning device of grain. *Agric. Mech. Res.* **2013**, *12*, 225–228.
22. Adamchuk, V.; Bulgakov, V.; Ivanovs, S.; Holovach, I.; Ihnatiev, Y. Theoretical study of pneumatic separation of grain mixtures in vortex flow. *Eng. Rural. Dev.* **2021**, *20*, 657–667.

23. Saitov, V.E.; Kurbanova, R.F.; Suvorov, A.N. Assessing the Adequacy of Mathematical Models of Light Impurity Fractionation in Sedimentary Chambers of Grain Cleaning Machines. *Procedia Eng.* **2016**, *150*, 107–110. [CrossRef]
24. Paun, A.; Stroescu, G.; Zaica, A.; Ştefan, V.; Olan, M.; Yasbeck Khozamy, S. Obtaining "organic seeds" of vegetable and industrial plants using the aerodynamic properties of the seeds. *Inmateh-Agric. Eng.* **2021**, *63*, 355–364. [CrossRef]
25. Hu, Z.; Zeng, H.; Ge, Y.; Wang, W.; Wang, J. Simulation and Experiment of Gas-Solid Flow in a Safflower Sorting Device Based on the CFD-DEM Coupling Method. *Processes* **2021**, *9*, 1239. [CrossRef]
26. Jasinskas, A.; Zvicevičius, E. *Biomasės Gamybos Inžinerija (Biomass Production Engineering)*; IDP Soliutions: Akademija, Lithuania, 2008; Volume 44. (In Lithuanian with English Summary)
27. Moskovskiy, M.N. Synthesis of System Solutions for the Technological Process of Obtaining Seeds on the Basis of Structural-Functional Modeling. Ph.D. Thesis, Kuban State Agrarian University, Krasnodar, Russia, 2017; p. 491.
28. Khamuev, V.; Gerasimenko, S.; Chaava, M. Engineering design of technological parameters of separation of seed in the upward air flow of pneumatic sorting machines. *E3S Web Conf.* **2019**, *126*, 00030. [CrossRef]
29. Ni, K.; Du, X.; Chen, S.; Chen, J.; Zhao, Y. Study on Grain Distribution in a Cross-flow Grain Separation Chamber Based on the Discrete Element Method. In Proceedings of the 2013 ASABE Annual International Meeting Sponsored by ASABE, Kansas City, MI, USA, 21–24 July 2013.
30. Jasinskas, A.; Steponavičius, D.; Šarauskis, E.; Šniauka, P.; Vaiciukevičius, E.; Zinkevičius, R. *Agricultural Machinery Laboratory Works*; Lithuania Agricultural University: Akademija, Lithuania, 2010; Volume 110.
31. Vaiciukevičius, E.; Šarauskis, E.; Jasinskas, A.; Sakalauskas, A.; Butkus, V.; Strakšas, A. Consistent patterns of detail movement in variable free air flow. *J. Food Agric. Environ.* **2010**, *8*, 370–374.
32. Witte, R.S.; Witte, J.S. *Statistics*; John Wiley & Sons: Hoboken, NJ, USA, 2017.
33. Vaiciukevičius, E.; Domeika, R.; Šarauskis, E.; Jasinskas, A.; Jasevičius, P.; Romaneckas, K. Research of pea seed sorting in the sloping air flow. *Actual Tasks Agric. Eng.* **2020**, *48*, 1–8.
34. Stepanenko, S.; Kotov, B.; Kuzmych, A.; Shvydia, V.; Kalinichenko, R.; Kharchenko, S.; Shchur, T.; Kocira, S.; Kwasniewski, D.; Dziki, D. To the Theory of Grain Motion in an Uneven Air Flow in a Vertical Pneumatic Separation Channel with an Annular Cross Section. *Processes* **2022**, *10*, 1929. [CrossRef]
35. Zewdu, A.D. Aerodynamic properties of the grain and straw material. *Biosyst. Eng.* **2007**, *46*, 304–309. [CrossRef]
36. Zhao, L.; Chen, l.; Yuan, F.; Wang, L. Simulation Study of Rice Cleaning Based on DEM-CFD Coupling Method. *Processes* **2022**, *10*, 281. [CrossRef]
37. Hharchenko, S.; Borshch, Y.; Kovalyshyn, S.; Piven, M.; Abduev, M.; Miernik, A.; Popardowski, E.; Kielbasa, P. Modeling of Aerodynamic Separation of Preliminarily Stratified Grain Mixture in Vertical Pneumatic Separation Duct. *Appl. Sci.* **2021**, *11*, 4383. [CrossRef]
38. Khamyev, V.; Gulyev, A.; Boiko, A. Justification of the design of pneumatic sorting machine for the preparation of selection seeds. In Proceedings of the International Conference on Modern Trends in Manufacturing Technologies and Equipment, Sevastopol, Russian, 30 October 2018; Volume 224, p. 05008. [CrossRef]
39. Nadimi, M.; Hawley, E.; Liu, J.; Hildebrand, K.; Sopiwnyk, E.; Paliwal, J. Enhancing traceability of wheat quality through the supply chain. *Compr. Rev. Food Sci. Food Saf.* **2023**, *22*, 2495–2595. [CrossRef] [PubMed]
40. Mykhailov, Y.; Zadosna, N.; Postnikova, M.; Pedchenko, G.; Khmelovskyi, V.; Bondar, M.; Ionichev, A.; Kozdęba, M.; Tomaszewska-Górecka, W. Energy assessment of the pneumatic sieve separator for agricultural crops. *Agric. Eng.* **2021**, *25*, 147–155. [CrossRef]