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The Process of Separation of Husked Soybean in Oblique Airflow

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Received: 10 August 2020; Accepted: 12 September 2020; Published: 14 September 2020

Abstract: The study concerns an evaluation of the effect of selected parameters on the course of horizontal pneumatic separation of unsorted husked soybean and the process efficiency. The efficiency of the process of isolating endosperm fraction from husks and other impurities was evaluated by determining the separation efficiency indicator η. It was shown that increased moisture content of the mixture results in a significant decrease in the η indicator. For example, with the 2.2% increase of moisture content (from W_1 = 10.1% to W_2 = 12.3%), the separation efficiency indicator decreased, on average, by 6.8%. The value of the η indicator rose with the increased velocity of the airstream, but the amount of valuable fraction that is picked up by the airstream is higher as well. It was found that, when the air velocity increased from $V_1 = 7.8\ \mathrm{m{\cdot}s^{-1}}$ to $V_2 = 10.5\ \mathrm{m{\cdot}s^{-1}}$ (for the moisture content W_1 = 10.1% and W_4 = 15.7%), the increment in the efficiency was the highest and reached 14.9–34.3%. A parametric model of the separation process of fragmented mixtures of biological origin was developed based on the analysis of the obtained results observation undertaken. This model can be used in designing and carrying out operations of separation into particular size fractions and cleaning of various feed mixtures, or in determining parameters of the movement of specific mixture components within pneumatic channels.

Keywords: pneumatic separation; husked soybean; mathematical model

1. Introduction

There are few publications related to the pneumatic separation of husked granular mixtures, especially those carried out with the use of a horizontal or oblique airstream in the scientific literature. Most of the publications focus on the use of many aerodynamic and mechanical features of the mixtures, which are used in complex cleaning machines of the air-sieve type. Sometimes the pneumatic separation of mixtures that are difficult to separate in the horizontal or vertical airstream is also used. Pneumatic separation is one of the most commonly used stages of pre-cleaning and sorting of grain mixtures, such as contaminated grains and seeds, as well as their fragmented mixtures, unsorted material after hulling, mixed herbs, and forest undergrowth. In these processes, airflow acts as the separating agent, which, thanks to the variable flow direction (horizontal, oblique, and vertical) and varying value of the flow rate, separates individual components of the mixture successfully and efficiently [1–3]. The accuracy and effectiveness of the airflow depend on the construction parameters of the separator, the nature of the airflow, and the uniformity of the supply of grain mixture into the working area of the air duct. In addition, the accuracy of separation of particles in the airflow depends on their aerodynamic drag, which is correlated closely with the shape and textural features of the surfaces (e.g., smooth, rough, ribbed, mesh, hair-covered surface, etc.) of separated elements.

Increase in cereal production corresponding to this development of agricultural products makes it necessary to construct more efficient processing machines and operations. This also concerns equipment for cleaning and sorting. Appropriate design of such machines for specific processes preparing raw material for processing depends on a number of factors, including physical properties of treated mixtures, as well as their individual components, required cleaning accuracy, or processing efficiency. At the same time, such requirements are set for the appliances themselves when it comes to the high sorting accuracy of output, the possibility of adjustment within a broad range of operating parameters, or a low noise level [4–9]. In a separation process of any agricultural product, several or even several dozens of separating characteristics are used in a sequence. In the case of small differences between-the-base materials and the impurities, it is important which impurity will be chosen to come first when the separation is started. Pneumatic separation is one of the methods of separating and cleaning grain materials. In the case of fragmented pulses, separation processes are relatively difficult to implement, since we are dealing here with an unusual material of heterogeneous biological nature [10–14]. These species discover great diversity and variability of physical features, even for the same cultivar. Hence, identification and isolation of the most important factors influencing the course and efficiency of the process of pneumatic separation of outer coats (hulls) from grain mixtures of various soybean varieties become essential. In this case, a flow of air acts as the working agent, which, thanks to varying flow rate, may be used for the separation of specific components from a mixture, cleaning, screening, and pneumatic conveying.

Aerodynamic properties of grain materials describe the behavior of the grain material in a vertical, oblique, and horizontal airstream. An example of this may be the research on numerical simulation of the separation process of whole sunflower seeds in the horizontal airstream [15,16]. Taking into account the differences in the geometry, dimensions, and shape of sunflower seeds in relation to the parameters of the hulled soybean mixture, it is very difficult to compare and refer to the results presented in this article. These properties are generally characterized by three coefficients, viz critical velocity, drag coefficient, and airflow resistance coefficient. Critical velocity is the velocity of vertical airflow, which provides a balance between the weight of a particle and the upward force of the airflow, which results in keeping the particle in suspension. The value of this feature is affected, among others, by the shape of the particle, the relationship between the weight and the cross-sectional area of the particle, as well as the surface texture of the particle that determines the drag in the airstream. In other words, a particle that is in a stream of air/gas/ is subject to the force of gravity and the pressure exerted by the air/gas/ on its surface. When these forces are at equilibrium the particle is suspended in the air/gas/, and the velocity of the air/gas/ at which this condition occurs is called the critical velocity or transport velocity. The critical velocity of a spherical particle can be derived from Formula (1):

$$\mathrm{u_{kr}} = \frac{\sqrt{4 \cdot d \cdot \rho s \cdot m}}{3 \cdot \lambda \cdot \rho g} \tag{1}$$

where d—diameter of the sphere (m); ρs—density of the material (kg·m^{-3}); ρg—air density (kg·m^{-3}); λ—drag coefficient of the environment; and m—particle weight (kg).

Airflow resistance is another parameter that characterizes the aerodynamic properties of a material. It is understood as the ability of a particle to resist airflow. It is described with an airflow resistance coefficient that is calculated by Formula (2):

$$\mathrm{k_o} = \lambda \cdot A \cdot \frac{\rho g}{12 \cdot m} \tag{2}$$

where A—surface of the particle (m), and m—weight of the particle (kg).

The abovementioned parameters relating to measuring and assessing the quality and effectiveness of the separation of grain materials, using an airflow, allow us to determine the numerical values of the sorting and cleaning process, as well as the technological efficiency of operating a particular apparatus. Depending on the processual and technological aspects, one can select the appropriate parameter. Single and multidimensional (with many factors), as well as multifactorial (one factor taking into account many elementary values), assessments are possible [2,17–20].

Pneumatic Sorting and Cleaning Systems Used in Cleaners and Agricultural Machinery

The process of pneumatic separation uses aerodynamic properties of particles as the separating parameter, wherein the critical velocity (transport velocity) is their characteristic property. Practice shows that, even for the same species of seeds, the value of critical velocity varies rather significantly. The greater the differences between the values of critical speeds of specific components the easier and more effective separation is [2]. The critical velocity decreases with the decrease of the density of the particles and their aerodynamic drag. This depends on the shape and surface characteristics of the surface (smooth, rough, ribbed, meshed, covered with hairs surface, etc.). The principle of separation of mixtures in an airflow is used in specialized pneumatic cleaners but also in threshing and seed-cleaning machines [21–24]. The wide use of this method of separation is justified by the simplicity of construction and operation of the equipment used for this purpose (Figure 1). Three main components of every universal machine for the thorough cleaning and sorting of seeds are air ducts, the screening unit, and Trieu sheet unit. As technology evolved, these devices were modified and adapted to requirements. Main differences between air ducts construction result from (1) direction of the airflow (horizontal, oblique, vertical, (2) position of the fan, and (3) airflow pressure (underpressure, overpressure, and combined) (Figure 1).

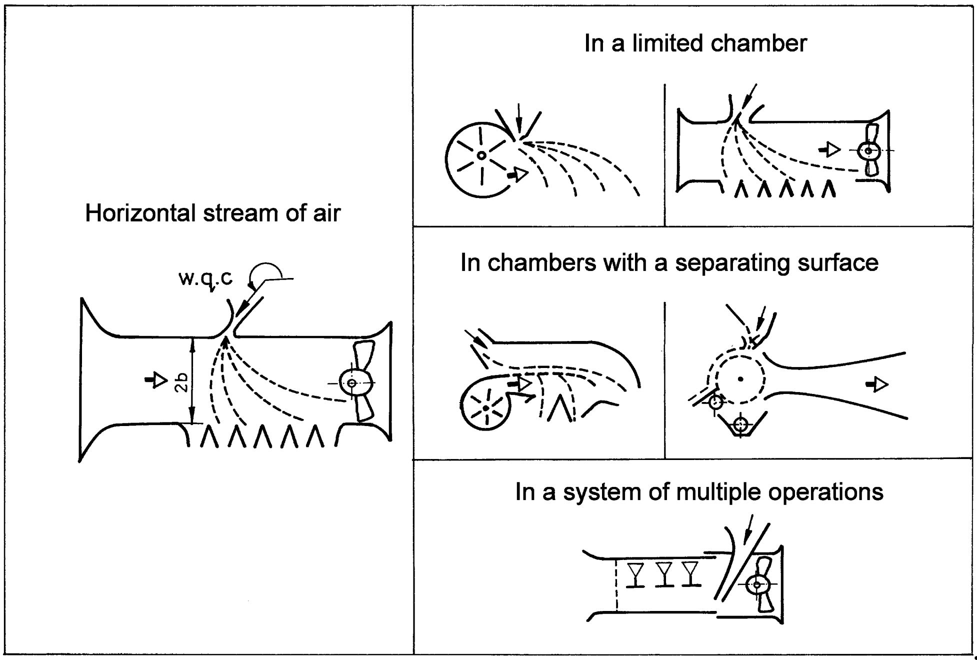

Figure 1. Schematic diagram of pneumatic systems with horizontal air ducts; b_k—width of the pneumatic duct, w—speed of feeding the grain mixture, q—quantity of mixture fed (duct load), and c—quantity characterizing the input pollution of the mixture.

The main objective of the study was to distinguish and identify the key parameters affecting the course and efficiency of separation of husked mixtures of Merlin variety soybean and to determine a theoretical relationship and correlation between various factors of the process. The efficiency of the process was assessed by determining the separation efficiency indicator η. Based on the obtained research results, a research task was formulated to develop a mathematical model of the separation process (separation and cleaning) of husked soybean mixtures in the airstream.

2. Materials and Methods

The study was conducted to determine the possibility of assessing the efficiency of the process of separating husked (fragmented) mixtures of soybean variety Merlin. Three size fractions of soybeans were distinguished i.e., the smallest, with an average size of 2.7 mm; intermediate, at 3.2 mm; and largest seeds, with the average size of 4.3 mm. The size of working slots were diminished by 0.2 mm for each of the three classes. Additionally, some preliminary results have demonstrated that, for these conditions, the fragmentation of endosperm was the smallest. Prior to the process of separating the husks from the endosperm, the soybean seeds were dehulled by using an under-runner disc huller with three working slots: s_1 = 2.5 mm, s_2 = 3.0 mm, and s_3 = 4.1 mm. From particular groups of the mixture, samples of 100 g each were weighed. Samples were taken 36 from a given slot, and then 3 from each moisture content. Dependently on harvesting conditions, the moisture of soy varies from 10% to 16%. Thus, the moisture levels selected in our study were closely related to the above range. The applied moisture levels were obtained by simple seeds watering and determined by a dry-oven method. These methods are simple and frequently used. Four final moisture levels were equal to W_1 = 10.1%, W_2 = 12.3%, W_3 = 13.8%, and W_4 = 15.7%. The grain size distribution was determined both for the whole seeds and for the fragmented mixture. Fractions of cotyledon (endosperm) and outer coat (hull) with fragments of non-detached cotyledons were manually isolated from the pneumatically separated fractions. The individual fractions were then weighed on an electronic balance, with the accuracy of 0.01 g. The research was carried out in three replications. On the basis of results obtained, the indicator of separation efficiency η was calculated by using Formula (3):

$$\eta = \frac{b}{b_o} \tag{3}$$

where *b* is the amount of impurities (hull fraction) contained in the fraction separated in the airstream (kg), and b_o is the amount of impurities in the input material (kg).

Pneumatic separators are intended for separating grain mixtures into particle size fractions, including hard-to-separate unsorted materials (mixtures of herbs and forest undergrowth), while at the same time removing all light and powdery organic and inorganic contaminants (Figure 2) [25]. The use of the testing stand allows the following to take place:

- Multiple repetitions of a pneumatic separation process in laboratory conditions and on a semi-industrial scale,
- Implementing a broad range of adjustability in the direction of airflow,
- Using a broad range of variation in the intensity of the airflow (laminar and turbulent flows),
- Separating multiple size fractions,
- Using a high-precision dispenser of granular and bulk materials to ensure uniformity of the feed of mixtures subject to separation into the working area,
- The testing stand is characterized by a relatively simple and lightweight design.

The working part of the testing station is mounted on a structure allowing for a broad range of adjustment of the angle of the separation device (a position from 0 to 30°).

A desirable feature of such a configuration is that, during the separation process, there are no damages nor changes in physical and biological properties of the mixtures treated. The study of pneumatic separation of dehulled mixtures was conducted with the working part of the separator inclined at 20°. The research was conducted for three velocities of the airflow: V_1 = 7.8 m·s^{-1}, V_2 = 10.5 m·s^{-1}, and V_3 = 12.8 m·s^{-1}. The optimal airflow speed was determined in some preliminary experiments. At the selected and applied herein speed, the highest efficiency of hull and endosperm separation was obtained. On the other hand, the waste of the endosperm fraction was the lowest. The obtained test results were statistically processed, ANOVA was performed, and surface plots were created, using distance weighted least squares.

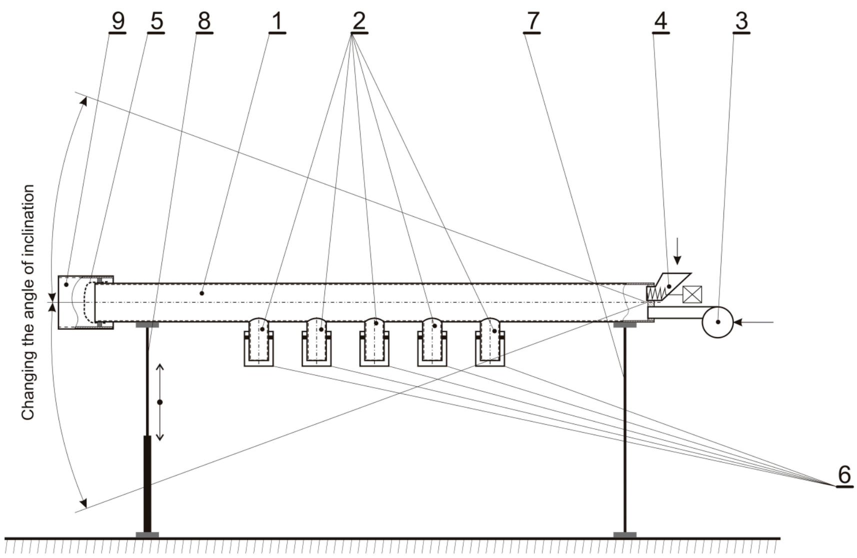

Figure 2. Schematic diagram of the test stand for cleaning and separation of plant materials in horizontal and oblique airflow: 1—pneumatic separator tube, 2—outlets for individual fractions, 3—ventilator with speed controller, 4—high-precision dispenser of the raw material for separation, 5—dust filter (fabric), 6—output trays for separated fractions, 7—back base of the separation tube, 8—front base of the separation tube (adjustable—telescopic), and 9—cleaned gas outlet [25].

3. Results

Based on the studies carried out, the values of the indicator η were calculated. They allow us to evaluate the efficiency of the separation process of husked soybean mixture in relation to the water content, the rate of fragmentation of the seeds, and the velocity of the airflow in the working area of the separator [26]. Figures 3–5 show the results obtained for the indicator η in the case of mixtures of fragmented soybean seeds of Merlin variety obtained for various slot widths of the husker and variable speed of the airflow. The relationships were generated by applying the standard mean squares method and procedures used by statistical software. Dependently on the statistical significance, their results allow us to conclude not only on the tested conditions but can demonstrate a more general tendency.

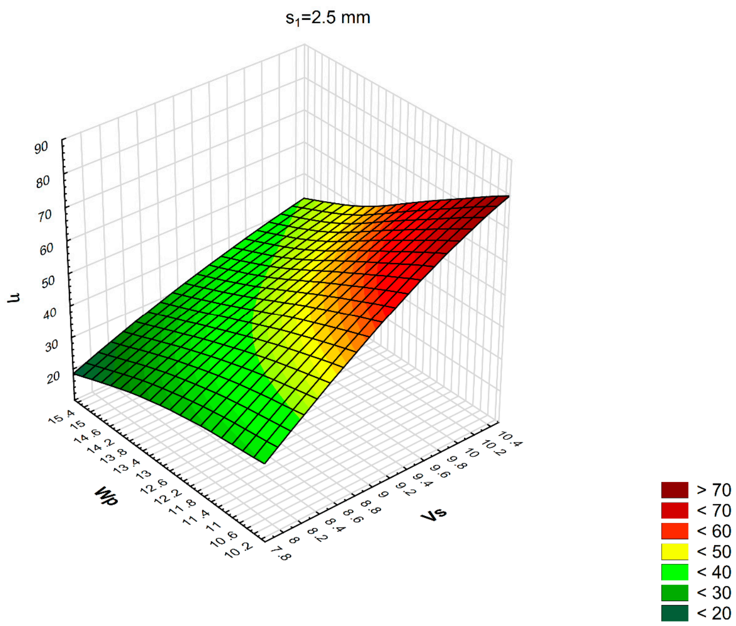

Figure 3. Separation efficiency indicator η for husked soybean mixtures: size fraction s_1 = 2.5 mm.

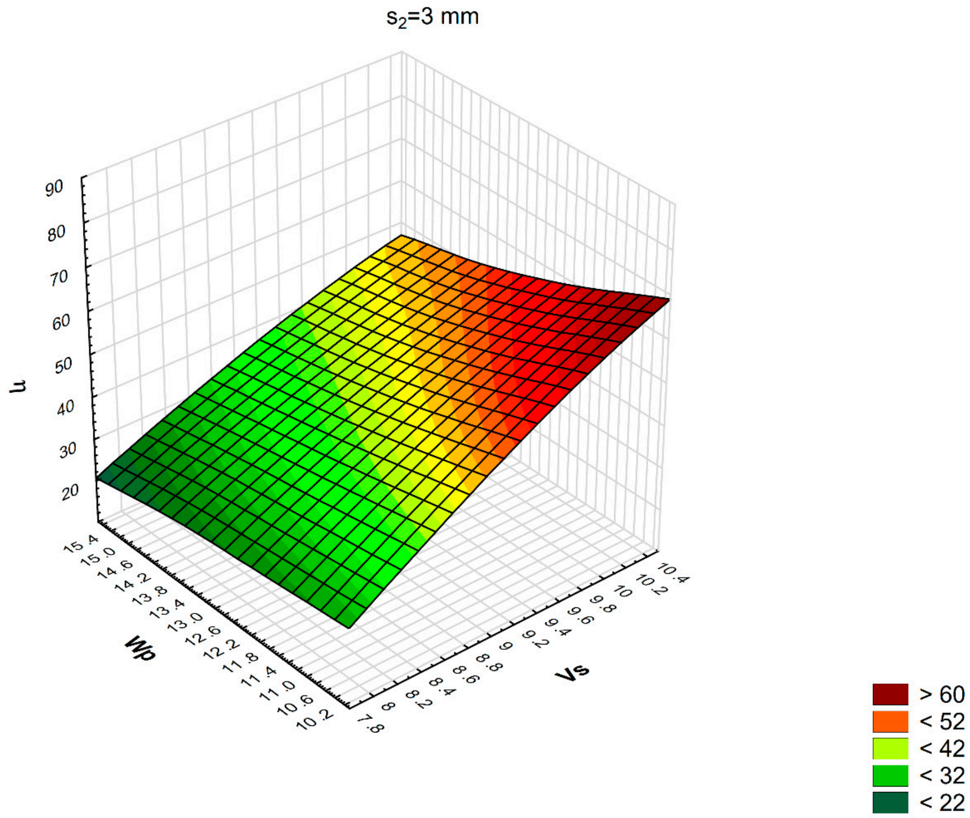

Figure 4. Separation efficiency indicator η for husked soybean mixtures: size fraction s_2 = 3.0 mm.

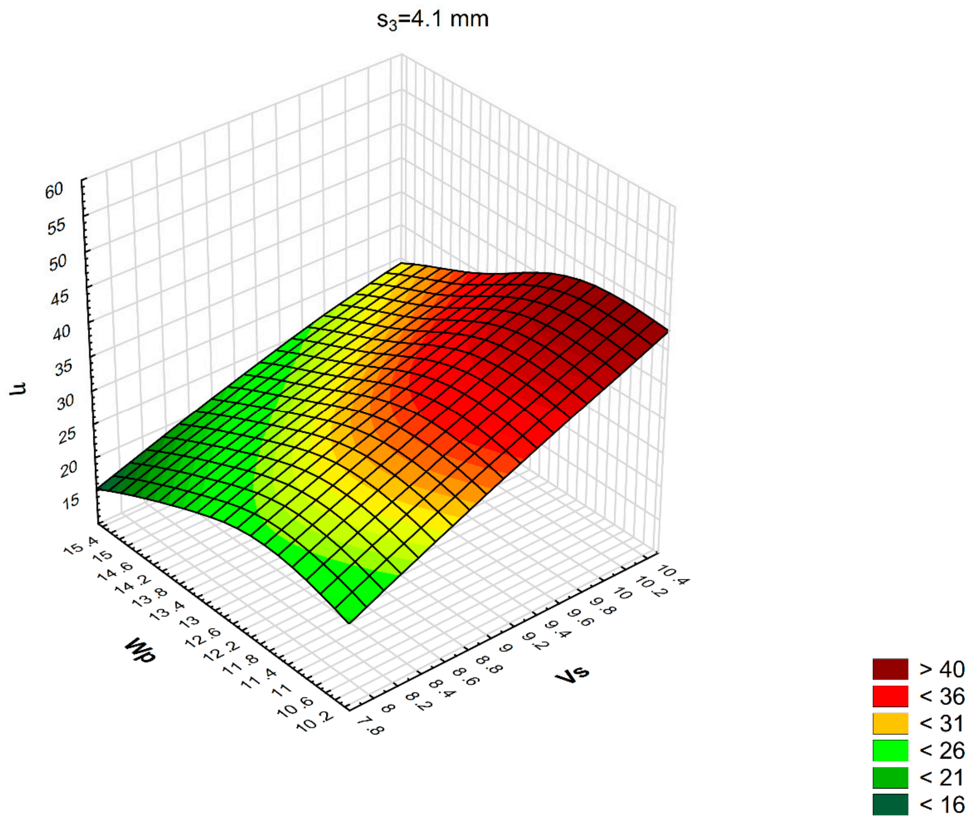

Figure 5. Separation efficiency indicator η for husked soybean mixtures: size fraction s_3 = 4.1 mm.

Our analysis of the obtained results of the separation efficiency indicator η shows a relatively varied correlation defining the relationship between the impact of examined parameters on the efficiency of the separation process of individual fractions. Similar relationships concerning the processes of cleaning and separation of husked mixtures of lupine, rape, cereals, and other leguminous and oilseeds were confirmed by other researchers [1,4,8,10,12,17,21,22]. It was observed that a little change in one of the parameters could lead to a substantial deterioration of the process, making it difficult to obtain stable separation efficiency conditions. The value of separation efficiency varied depending on the moisture content of the samples, the degree of fragmentation, and the intensity of the airflow in the separator duct. Its highest value, i.e., $\eta = 87.1\%$, was obtained for the grain mixture with the moisture content of $W_1 = 10.1\%$, the working slot $s_1 = 2.5$ mm, and the velocity of airflow $V_1 = 12.8\ \mathrm{m \cdot s^{-1}}$. Similar results were obtained in the case of the separation of the husk and cleaning of the endosperm from dehulled mixtures of various lupine varieties [13]. In other studies [16], the separation of pollutants from dimensionally sorted whole sunflower seeds was carried out. The studies were carried out on a pneumatic separator with a horizontal airstream. In this case, the authors obtained the highest separation and separation coefficient for an air flow velocity of 15 m $\mathrm{s^{-1}}$ and particles with an average size of 3 mm. The separation of larger particles (3 and 7 mm) required a significant increase in the airflow velocity. These researchers analyzed the separation coefficient, not the separation efficiency. Of course, these coefficients are correlated with each other, but their direct comparison is problematic. Aliev and others [16] have shown that the separation coefficient increases with the velocity of the airstream, similar to our research, but other relationships and parameters are different. There are also greater losses of valuable material (endosperm) going to the waste zone. In the presented studies, higher values of the separation efficiency coefficient were obtained for more fragmented samples of the mixture (or smaller particles of the raw material) and lower for larger ones, which, in the case of the works [16], cannot be stated. There was no attempt to correlate the obtained results with the moisture content of the raw material, which, as shown in the presented results of the article, have an impact on the separation efficiency. As the moisture content of the mixture increased, the effectiveness of the separation of the outer cover fraction decreased significantly. For the moisture content $W_4 = 15.7\%$, working slot $s_3 = 4.1$ mm, and airflow velocity $V_1 = 12.8\ \mathrm{m \cdot s^{-1}}$, the indicator η reached just 33.1%. It can be noted that a change in any of the separation parameters led to a decline in the values of η indicator. This applies also to the intensity of the airflow when increased beyond the threshold of 12–13 $\mathrm{m \cdot s^{-1}}$. Although the higher value of the airflow increased the efficiency of separating the fraction of outer coat from cotyledons, this was achieved at the expense of an increased amount of the valuable fraction present in the debris. For example, at the airstream velocity $V_1 = 7.8$ m $\mathrm{s^{-1}}$ and $V_3 = 12.8$ m $\mathrm{s^{-1}}$ (within the moisture $W_1 = 10.1\%$ and the working gap $s_2 = 2.5$ mm, its highest increase varied in the range of 14.9–34.3%. Hence the conclusion that the upper limit of the airflow velocity equal to $V_3 = 12.\mathrm{m \cdot s^{-1}}$ is the optimal value for these research material. For example, with a set of working gap ($s_1 = 2.5$ mm) and airstream velocity $V_1 = 7.8\ \mathrm{ms^{-1}}$, the differences in the values of the coefficient η for individual moisture levels for dry samples were $W_1 = 10.1\%$, respectively—($\eta = 54\%$), for $W_2 = 12.3\%$—($\eta = 47.2\%$), for $W_3 = 13.8\%$—($\eta = 33.4\%$), and for wet samples $W_4 = 15.7\%$ the value of the coefficient was 34.6%. Analysis of the indicator η undoubtedly confirmed that the moisture content of the fragmented mixture has a significant impact on the efficiency of the process of separation into individual fractions. In the case of the Merlin variety mixture, the highest value of η was equal to 87.1%.

When analyzing the results of the studies on the process of separating cotyledons (endosperm) from remaining impurities, it should be concluded that, in the case of hulled (fragmented) mixtures of soybean of Merlin variety, the increase in separation efficiency was at the expense of an increased share of the valuable endosperm fraction in the debris, which was an adverse effect resulting in increased losses.

Development of a Mathematical Model for the Research Results

Before developing a separation and cleaning model of compound grain mixtures, it is advisable first to have the most comprehensive input data regarding the grain mixture (input material) and then to determine the required outcomes (output data). At this stage, it is also important to make an attempt to determine the relationships and correlations occurring between the input and output datasets, as the basis for further modeling. The fundamental technological goal of the separation process may be defined in many different ways, and, therefore, its final evaluation can be analyzed by considering various indicators of efficiency and quality. Most commonly they represent the processing outcomes in the form of numerical values. These most often include the process efficiency and the amount of the maximally separated impurities. Often for cleaning and separation processes of bulk mixtures, there is a need for the simultaneous determination of several technological parameters that characterize the final effect of the treatment. This can be exemplified by the evaluation of a grain-milling process in terms of its efficiency and the precision of separation of the ground mixture into individual milling fractions, with simultaneous measurement and analysis of the energy consumption of both the milling process and the separation (screening) process. All of these technological outcomes of separation and cleaning operations could form the database for assessing the performance of the processing equipment itself. Thus, in order to evaluate the technological effects of the separation and/or cleaning process of biological origin, varied criteria can be adopted. On one hand, they are associated with the course and efficiency of the separation process itself, while on the other hand, they are associated with characteristics of a. Thus, the efficiency of the separation process Q relates the actual amount of impurities present in the input material subject to separation Z_r, to the actual amount of these impurities Z_f separated by the working elements of the cleaning machine. The overall technological separation effect of a mixture composed of number of components in order to isolate n number of particular fractions can be described with the following general formula, Formula (4):

$$E_t = \sum_{i=1}^{n} \mathrm{W}_i \frac{\varphi_{ii-}a_i}{a_{ii} - a_i} \tag{4}$$

Equation (4) shows the ratio of the actual increase of the concentration of the *i*-th component of the mixture to the final, most efficient separation. As already noted, the separation processes of mixtures of biological origin are most often defined by a number of relevant below-mentioned groups of parameters characterizing inter alia:

- Applied technological schemes of the cleaning operations,
- Principles and working conditions of the cleaning machines (screen size, air velocity and capacity, wear, etc.),
- Size, geometry and other physical characteristics of individual components of the mixture subjected to separation,
- Amount of various impurities in the mixture subject to separation.

A parameter diagram of the separation process comprising the main input and output parameters of the process and selected factors facilitating or interfering with the course and efficiency of the process is presented in Figure 6.

The output parameters of the process should be treated as the final result of its efficiency.

The efficiency of the separation process may be additionally affected by some environmental conditions at which the process is implemented. Due to the high specificity of conducting separation processes of various materials, they were not included in the above model. The mathematical model of the separation process should meet its objectives as well as possible, and, therefore, already at the initial stage of its development, it is very important to formulate and determine all parameters and factors that might influence the processing outcomes. Such an exemplary goal may be to establish procedures and anticipated correlations and influence of selected factors of the separation process in relation to its duration (static concern), or the relationships occurring during the transition from one predetermined regime into another one (dynamic characteristics concern). Therefore, all the initial assumptions and main scheduled expectations from the model, including the optimization aspects, should be formulated by considering the applicable laws of kinetics, statistics, and dynamics.

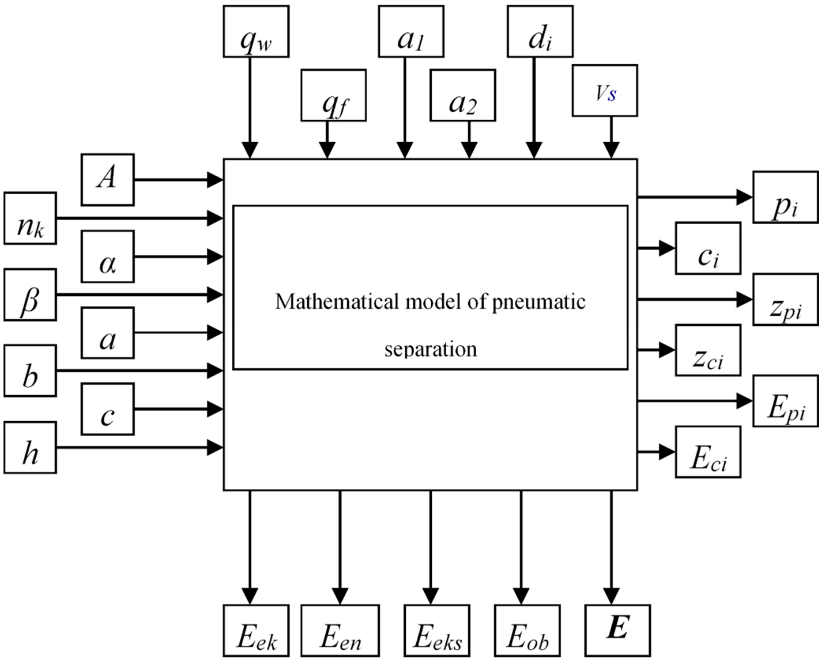

Figure 6. A parametric model of the separation and cleaning process of a grain mixture of biological origin [5].

4. Conclusions

1. Different values of the coefficient η were noted, depending on the moisture level of the processed raw material. For example, with a set working gap (s_1 = 2.5 mm) and airstream velocity V_1 = 7.8 ms^{-1}, the differences in the values of the coefficient η for individual humidity levels for dry samples were W_1 = 10.1%, respectively—(η = 54%), for W_2 = 12.3%—(η = 47.2%), for W_3 = 13.8%—(η = 33.4%), and for wet samples W_4 = 15.7%, the value of the coefficient was 34.6%. A similar, significantly decreasing trend for this parameter at different levels of raw material moisture was noted for the crushed samples obtained in the working slots of the husker s_2 = 3.0 mm and s_3 = 4.1 mm.
2. With regard to the three sizes of the husking gaps used, significant fluctuations in the value of the coefficient η were noted. For example, for the working gap of the hulling machine s_3 = 4.1 mm and the adopted ranges of airstream velocity V_1 = 7.8 m s^{-1}, V_2 = 10.5 m s^{-1}, and V_3 = 12.8 m s^{-1}, the differences in the coefficient values were, respectively, 7.4%, 11.8%, and 24.9%. When using the working gap s_1 = 2.5 mm and analogous other parameters, the η values increased by 14.9%, 39.8%, and 34.3%, respectively. The analysis of the research results shows a large influence of the size of the husking working gap on the course and effectiveness of the separation of the cotyledon fraction from the endosperm fraction, carried out under these conditions.
3. Increasing the speed of the airstream led to the increase of the coefficient η. At the same time, an unfavorable—from the point of view of separation and cleaning technology—phenomenon of an increase in the amount of valuable fraction (cotyledon fraction—endosperm), which is carried away by the stream and directed to waste, was noted. For example, at the airstream velocity V_1 = 7.8 m s^{-1} and V_3 = 12.8 m s^{-1} (within the humidity W_1 = 10.1% and the working gap S_2 = 2.5 mm, its highest increase varied in the range of 14.9–34.3%.

4. Based on the analysis of the obtained research results and observations, a parametric model of the separation and cleaning process of dehusked (crushed) soybean seeds was developed. It can be used in planning and carrying out pneumatic separation and calculating the parameters of the movement of particles of individual components of granular mixtures in pneumatic channels with horizontal and oblique airstream.
5. The proposed research methodology, conditions, and possibilities of changing the range of separation parameters and the designed test stand can be used to separate the husk from the endosperm for other dehusked mixtures, e.g., legume seeds (pea, lupine, horse bean, etc.) or for cleaning herbs and undergrowth.

Author Contributions: All authors contributed equally to this paper. All authors have read and agreed to the published version of the manuscript.

Funding: Funded by the "Excellent science" program of the Ministry of Science and Higher Education, as a part of the contract no. DNK/SP/465641/2020, "The role of the agricultural engineering and environmental engineering in the sustainable agriculture development".

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

η	efficiency of the separation (%);
b	amount of impurities (husk fraction) contained in the fraction separated in the airstream (kg);
b_o	amount of impurities in the input material (kg);
V_s	airflow speed ($m \cdot s^{-1}$);
W_i	amount of the *i*-th fraction (kg);
W_p (W_1, W_2, W_3, W_4)	samples moisture content of (%);
φ_{ii}	purity of the separated *i*-th fraction (the content of the *i*-th component of the mixture in the *i*-th fraction (kg));
s_1, s_2, s_3	width of the slots in the shredder (mm);
a_i	content of thei-th component of the mixture in the input mixture intended for cleaning (kg);
a_{ii}	purity of the *i*-th fraction possible to separate in a full, one hundred percent separation (%);
Q	efficiency of the separation process ($kg \cdot h^{-1}$);
Z_r	mixture intended for separation (kg);
Z_f	actual amount of impurities separated by the cleaning machine (kg);
n_k	number of components in the mixture;
m	weight of the mixture fraction (kg);
q_w	load on the working elements of the cleaning machine referred to the unit of their width ($kg \cdot m^2$);
q_f	load on the working elements of the cleaning machine referred to their overall area ($kg \cdot m^2$);
d_i	dimensions and shape of the sieve openings (m);
V_c	initial velocity of the particles ($m \cdot s^{-1}$);
A	vibration amplitude of the working element (m);
n	vibration frequency of the frame with the set of sieves (s);
α and β	angle of inclination of the working plane relative to the horizontal and vertical planes;
a_k, b_k, c_k, and h_k	geometric dimensions of pneumatic channels (m);
p_i	amount of screened component (kg);
c_i	amount of screenings (kg);
z_{pi}	amount of impurities in any random size fraction (kg);
z_{ci}	amount of screenings in any random size fraction (kg);

E_{pi}	technological effectiveness of fraction separation (%);
E_{ci}	technological effectiveness of screenings separation (%);
E_{ek}	economic evaluation index (%);
E_{en}	energy evaluation index (%);
E_{eks}	operating index (%);
E_{ob}	machines operation efficiency index (%);
E_t	comprehensive discriminant of the evaluation of effectiveness of the separation process (%).

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