RESEARCH ON SUNFLOWER SEEDS SEPARATION BY AIRFLOW / ДОСЛІДЖЕННЯ ПРОЦЕСУ СЕПАРАЦІЇ НАСІННЯ СОНЯШНИКУ ПІД ДІЄЮ ПОВІТРЯНОГО ПОТОКУ

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ABSTRACT

Investigation of the process of sunflower seeds separation during its movement under the influence of air flow has been carried out in two stages. The first (theoretical) stage is implemented in the software package STAR-CCM+ using the corresponding physical models. The second stage has been made to carry out the experimental research on the installation with the base of the aerodynamic separator of the "Almaz" series. The results of numerical simulation and experimental researches of the sunflower seed separation process during its movement in the airflow are presented. As a result of numerical simulation and experimental studies of the mechanical and technological process of sunflower seeds separation during movement under the influence of air flow, there has been developed the dependences of the distribution of each seed fraction on the length of the area (average value, average square deviation, filling factor, distribution coefficient) and the consumed power from the seed effective diameter, air flow velocity and the seed supply. Statistical analysis has showed that the correlation coefficient between the theoretical and experimental dependencies in the variation of the factors' values in the given range is 0.96. During the research, a compromising problem was solved, namely, there had been reached minimization of consumed power at the maximum value of the distribution coefficient and the seed supply.

РЕЗЮМЕ

Дослідження процесу сепарації насіння соняшнику при його переміщенні під дією повітряного потоку проводились в два етапи. Перший (теоретичний) етап реалізовано в програмному пакеті STAR-CCM+ з використанням відповідних фізичних моделей. Другим етапом було проведення експериментальних досліджень на установці із базою аеродинамічного сепаратора серії «Алмаз». Представлені результати чисельного моделювання і експериментальних досліджень процесу сепарації насіння соняшнику при його переміщенні під дією повітряного потоку. В результаті чисельного моделювання і експериментальних досліджень механіко-технологічного процесу сепарації насіння соняшнику при його переміщенні під дією повітряного потоку отримані залежності розподілу кожної фракції насіння по довжині області (середнє значення, середньоквадратичне відхилення, коефіцієнт заповнення, коефіцієнт розподілу) і споживану потужність від ефективного діаметра насінини, швидкості подачі повітря та подачі насіння. Статистичний аналіз показав, що коефіцієнт кореляції між теоретичною і експериментальною залежностями при варіюванні значеннями факторів в заданому діапазоні складає 0,96. В процесі досліджень була вирішена компромісна задача, а саме мінімізація споживаємої потужності при максимальному значенні коефіцієнта розподілу і подачі насіння.

INTRODUCTION

The unsatisfactory quality of sunflower seeds results in a significant reduction in agricultural productivity and a high over expending of seed material *(Zaika P., 2006).* According to the current standards, oilseed crop varieties and crop yields are determined mainly by their varietal purity, which should equal 99.6-99.9% for the elite seed (elite, superelite) - depending on the crop *(Aliev E., 2016).*

The task of separating sunflower seeds by density (specific weight, texture) is reduced to its previous calibration by geometric dimensions *(Tishchenko L., Olshansky V., Olshansky S., 2010)*. In other words, there are two variables: sailing and density. It is obvious that at the seed with same density and smaller mass flies further under the air flow influence, than seeds of greater mass that fly shorter distances.

In addition, depending on the orientation of the seed to the vector of the air flow velocity, the sailing range appears, which leads to a random trajectory of the movement of seeds *(Nurullin E., Salakhov I., Dmitriev A., 2014)*. Of course, within the long-term airflow impact, the seed will take the best aerodynamic position in which the lowest resistance is observed *(Aliev E., Shevchenko I., 2017)*.

In addition to the above, the air flow must have a uniform structure, in terms of the turbulence parameters (scale and intensity), and on the speed diagram *(Aliev E., Yaropud V., 2017)*.

Considering all the difficulties of the task, the process of sunflower seeds separation during their movement under the air flow influence must be theoretically and experimentally explored.

MATERIALS AND METHODS

Investigation of the process of sunflower seeds separation during their movement under the influence of air flow has been carried out in two stages.

The first (theoretical) stage is implemented in the software package STAR-CCM+ using the corresponding physical models. The initial positions and velocities of sunflower seeds and the air flow have been determined using the finite element method. Then, based on this initial data, given physical laws of contact interaction, the forces acting on each seed at each interval of time have been calculated. For each seed, the resulting force has been calculated and the Cauchy problem has also been solved on the selected time interval, the result of which is the initial data for the next step. The following physical models have been selected for numerical modeling: k-ε disturbed flow turbulence model, gravity field, Van der Waals real gas model, discrete element model, multiphase interaction model *(Aliev E., Bandura V., Pryshliak V., Yaropud V., Trukhanska O., 2018)*. The method of discrete elements is based on the laws of conservation of impulse and impulse momentum for Lagrangian models of a multiphase environment. However, to construct a physico-mathematical model, one must assume that the seeds are represented in the form of identical ellipsoids with a defined density and effective diameter.

According to previous researches of physical and mechanical properties of Prometheus variety sunflower seeds, selected by the Institute of Oilseeds of NAAS, *(Burenko K., Vedmedeva E., Pershin A., 2012; Aliev E., Shevchenko I., 2017; Aliev E., Yaropud V., 2017)* the following averaged values were adopted for numerical modeling: Poisson's coefficient – 0.5; Young's modulus – 0.2 MPa; density – 200-1000 kg/m^3; coefficient of friction of rest – 0.8; normal recovery factor – 0.5; tangential recovery factor – 0.5; coefficient of rolling resistance – 0.3. Properties of the environment have been fixed as follows: environment – air; dynamic viscosity – $1.85508 \cdot 10^{-5}$ Pa·s; Prandtl's turbulent number – 0.9; free fall acceleration – 9.8 m/s^2; temperature – 293 K; pressure – 101325 Pa. The size of the grid cell modeling is 0.001 m. The exposure is from 3 to 7 s.

For the implementation of numerical simulation, a computational scheme of sunflower seed separation process has been made when it was moved under the air flow influence (Fig. 1).

For the factors of numerical modeling, the following most important technological parameters have been adopted: seed effective diameter D_p, air supply rate V, seeding Q.

The effective diameter of sunflower seed D_p was determined by the formula

$$D_p = \sqrt[3]{l_x \cdot l_y \cdot l_z} \tag{1}$$

where: l_x, l_y, l_z – length, width and thickness of sunflower seed, respectively, mm.

According to researches *(Vedmedeva K., Makhova T., Kirpichova N., 2017),* the geometric dimensions of sunflower seed are l_x = 8-15 mm, l_y = 3-8 mm, l_z = 2-4 mm, so it can be stated, that the effective diameter of sunflower seeds D_p varies in the range of 3-7 mm. Due to the fact that the seeds can be integral, partial and empty, then, according to researches *(Vedmedeva K., Makhova T., Karpychova N., 2017)*, their density can vary in the range of 200-1000 kg/m^3. Therefore, the seed flow has been represented by 5 fractions, the weight of 1000 seeds of each being presented in Table 1.

Table 1

Weight of 1000 seeds for a determined effective diameter m_{1000}, g

Effective diameter of seed D_p, mm	Seeds density ρ, kg/m^3				
	200	400	600	800	1000
3	3	6	9	12	15
5	13	26	39	52	65
7	36	72	108	144	180

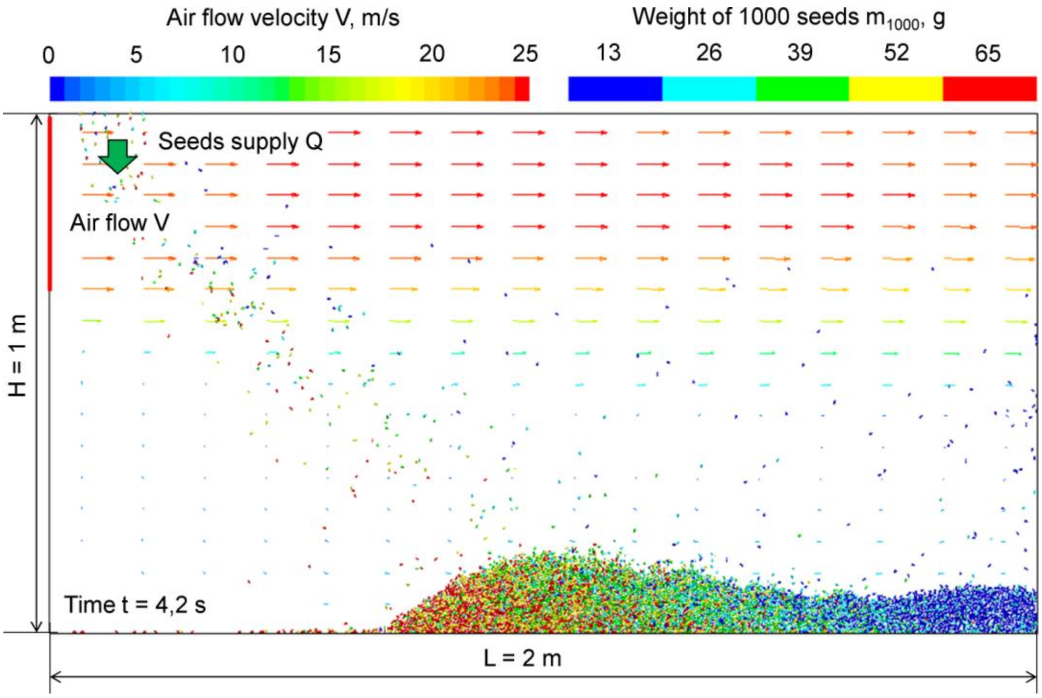


Fig. 1 – Scheme of numerical simulation of the sunflower seed separation process during its movement under the air flow influence

Numerical simulation has been conducted on a complete factorial study with a total number of experiments – 3^3 = 27. The numerical modeling factors variation boundaries are presented in Table 2 based on the previous studies *(Aliev E., 2017)*.

Table 2

Factors variations levels in numerical simulation of the seeds movement in the air flow

Factors variations level	Factors		
	Seeds' effective diameter D_p, mm	Seeds supply Q, kg/s	Air flow velocity V, m/s
Top level (+)	7	0.09	25
Base level (0)	5	0.06	20
Low level (–)	3	0.03	15
Factors variations interval	2	0.03	5

As a result of the seeds separation under the air flow influence, the distribution of each fraction along the length of the area can be represented by a normal distribution with a defined value and a value deviation *σ* (fig. 2). For a normal distribution in the area, a probability of 95.45 % is observed.

According to fig. 2, the best separation (95.45 %) is achieved with the condition:

$$2\sigma_1 + 2(2\sigma_2 + 2\sigma_3 + 2\sigma_4) + 2\sigma_5 \le \bar{x}_5 - \bar{x}_1 \quad (2)$$

or

$$\theta = \frac{\bar{x}_5 - \bar{x}_1}{2\sigma_1 + 2(2\sigma_2 + 2\sigma_3 + 2\sigma_4) + 2\sigma_5} \to \max \quad (3)$$

where: θ – filling factor.

It should be noted that the entire area has been divided into 20 identical vertical zones, each of which determines the amount of seeds in each fraction.

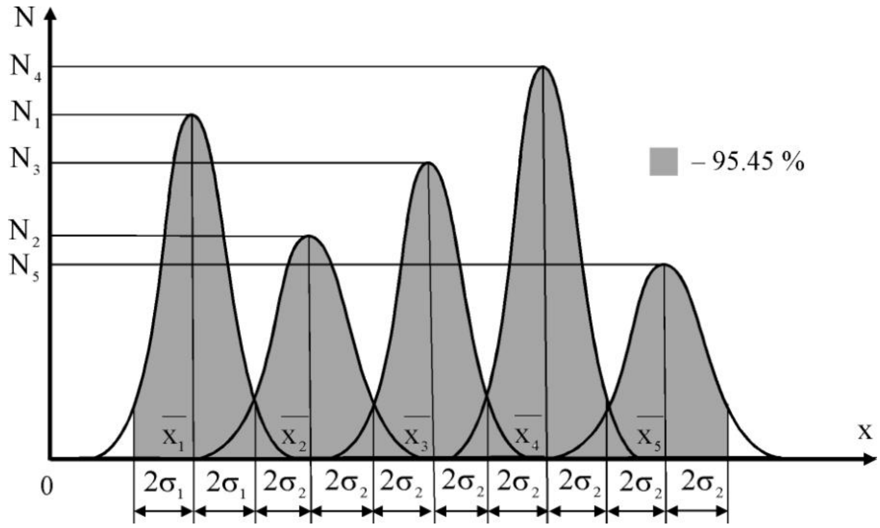


Fig. 2 – Functions of normal distribution of each fraction by area length

The fill factor *θ*, mentioned before, means values of the fractions distributions in length and their square deviations *σ* characterize the size and location of the gathering areas (samplings). However, in existing aerodynamic separators, preservatives of the same size are used, which complicates the assessment of the separation process quality. Therefore, another criterion for the quality of fractions distribution in the receptacles is introduced – the distribution coefficient δ, which is defined as follows. Let the input material be divided into *N* fractions, then the number of gatherable areas should be *N*. For each fringe area, the fractional composition of the seed mixture is determined, which can be mathematically represented in the form of a square matrix *NxN*:

$$\begin{pmatrix} w_{11} & w_{12} & \dots & w_{1N} \\ w_{21} & w_{22} & \dots & w_{2N} \\ \dots & \dots & \dots & \dots \\ w_{N1} & w_{N2} & \dots & w_{NN} \end{pmatrix} \tag{4}$$

where: w_{ij} – mass fraction of fraction i in the collection j:

$$w_{ij} = \frac{m_{ij}}{\sum_{i=1}^{N}\sum_{j=1}^{N} m_{ij}} \cdot 100\% \tag{5}$$

m_{ij} is the mass of fraction i in the collection j.

The distribution coefficient δ is defined as the largest sum of the diagonal elements of the matrix (4):

$$\delta = \max\left(\sum_{k=1}^{N} w_{kk}, \sum_{k=1}^{N} w_{k(k+1)}, \dots, \sum_{k=1}^{N} w_{k(k+N-1)}, \sum_{k=1}^{N} w_{(k+1)k}, \dots, \sum_{k=1}^{N} w_{(k+N-1)k} \right) \tag{6}$$

where: *k* is a natural number.

The second stage has been made to carry out the experimental research on the installation with the base of the aerodynamic separator of the "Almaz" series (produced by the PE PF "Agrotech"), consisting of a bunker *1* for loading seed material to be separated from a vibroplate *2*, generator of air jet cascades *3,* which is installed below it and connected to the pressures air flow source *4* into generator *3* and separation chamber *5*. Under the separation chamber *5* are the collections of fractions *6* (I-IV). A collection of dust and light fraction *7* (V) was mounted at the end of the separation chamber *5*. The design and technological scheme and the general view of the experimental installation are presented in Fig. 3. To ensure a certain supply of seeds, a calibrated valve *8* is used to limit input performance. The specified air supply is set using the *9* (Danfoss VLT Micro Drive) frequency converter, and controlled using the anemometer *10* (Benetech GM-816).

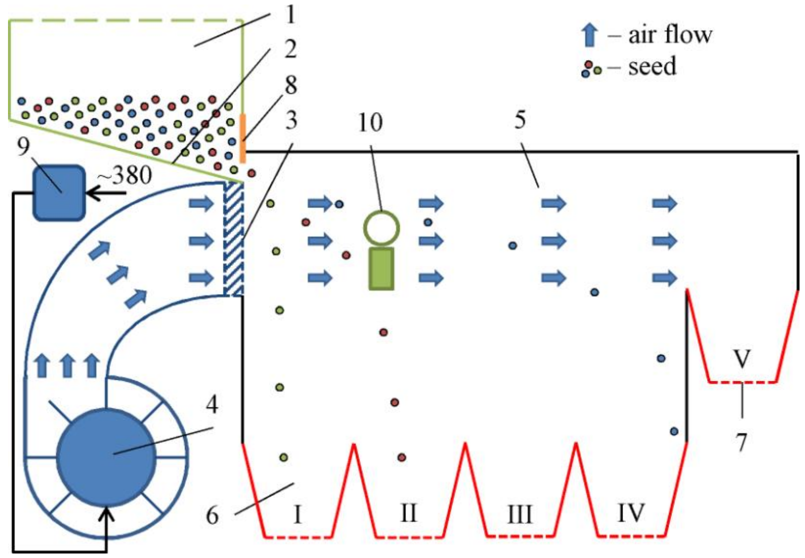
The source material during the experimental researches was represented by sunflower seeds of the Prometheus variety, selection of the Institute of Oilseed Crops NAAS, which were calibrated to a fraction of

3.2-3.4 mm. One experiment was conducted by passing through a pilot sample of a supply unit of 100 kg of seeds.

Factors for experimental studies are the air supply rate *V* and the supply of seed *Q*. The intervals and levels of variation by these factors coincide with the theoretical ones (Table 1).

As optimization criteria were adopted: power consumption – *P*, kW and distribution coefficient – *δ*. The power consumed by the fan drive is measured using one of the additional functions of the Danfoss VLT Micro Drive frequency converter. Since the task of separating sunflower seeds during its movement under the influence of air flow is the division into 5 fractions (integral, partial, naked core, empty and dust), then at the experimental installation exposed 5 fence regions. For each experiment, for each fringe area, fraction composition is determined according to the generally accepted methodology (GOST 10854-88, 2010) and the corresponding distribution coefficient δ is calculated according to the formula (6).

Experimental studies have been conducted on the *D*-optimal second-order Boxing-Benkin plan for 2 factors (9 trials) in a three-time repetition. The processing of the research results has been carried out by the mathematical factor planning of experiments method, using the Mathematica software package. The mathematical model is determined by one optimization criterion.



a

b

Fig. 3 – Structural-technological scheme (a) and general view (b) of an experimental plant for studying the process of sunflower seeds separation when they are displaced by airflow

1 – bunker; 2 – vibroplate; 3 – air jets oscillator; 4 – fan; 5 – separation chamber; 6 – collections of fractions; 7 – dust collector and light fraction; 8 – valve; 9 – frequency converter 10 – anemometer

RESULTS

According to the first stage, as a result of numerical simulation, a visualization of the technological process of sunflower seeds separation was obtained when they were displaced under the influence of air flow (fig. 4).

The average value and the average square deviation σ have been calculated for each experiment, for each fraction of seeds accordingly. According to the data obtained by formula (3), the filling factor θ is calculated. Using Mathematica software package, a mathematical expression is compiled in a skilled form after the reduction of non-significant parts of the equation according to Student's criterion, which links the coefficient of filling θ with the research factors:

$$\theta = 0.658343 - 0.065448\,D_p - 0.00711689\,D_p^2 - 4.31791\,Q + 0.00181584\,V + \\ + 0.00683085\,D_pV + 0.159939\,QV - 0.00138784\,V^2 \quad (7)$$

The graphical interpretation of the dependence (7) is shown in Fig. 5. The optimum parameters of equation (7) under the condition of the maximum filling factor *θ* are D_p = 3 mm, *Q* = 0.03 kg/s, V = 15 m/s. As it can be seen from Fig. 5: with the increase of the seed diameter D_p, the fill factor θ decreases by parabola; with an increase in the seeds supply *Q*, the fill factor θ decreases linearly; and for the air flow velocity *V* = 15 m/s, the optimal value of the fill factor *θ* is present.

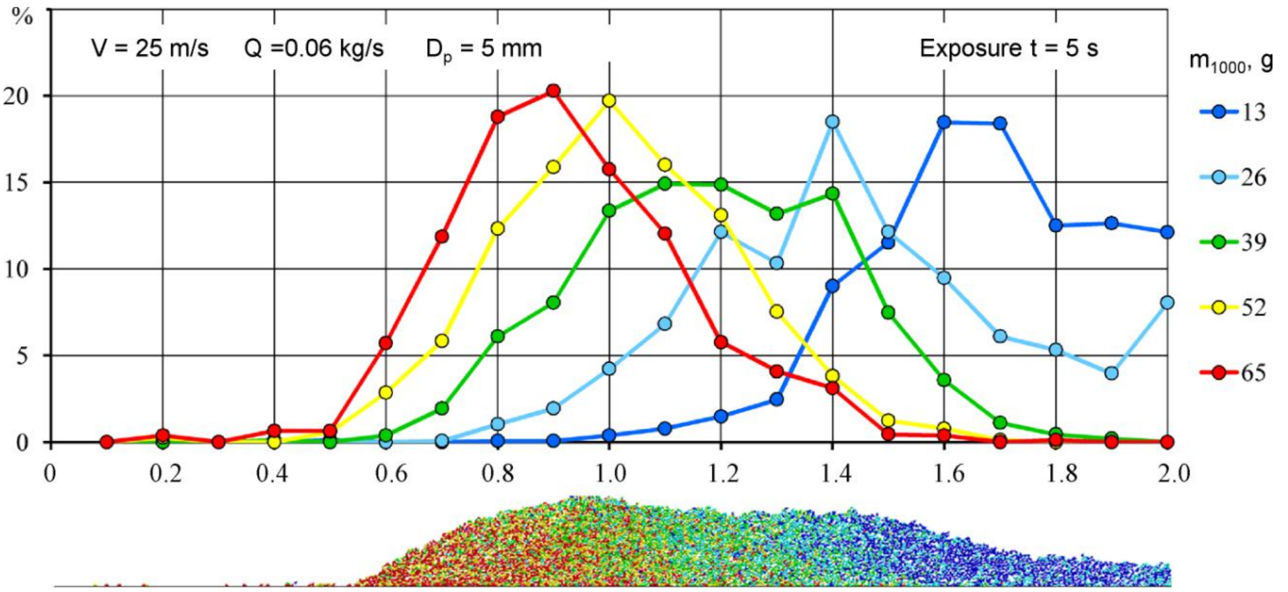


Fig. 4 – Distribution of seed fractions with effective diameter D_p = 5 mm along the length of the area formed by the air flow influence

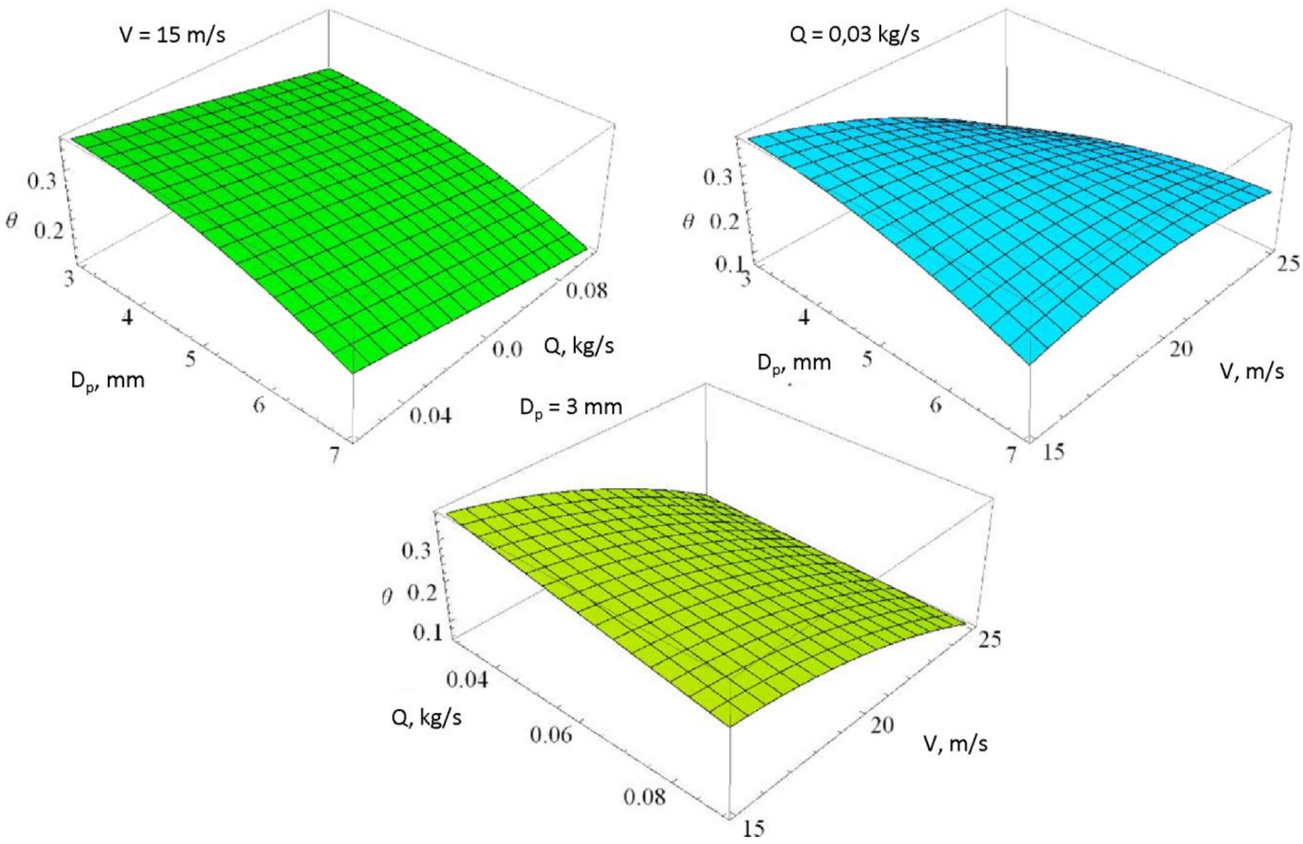


Fig. 5 – The dependence of the filling factor θ on the effective diameter of the seed D_p, the supply of seed Q and the air velocity V

According to the obtained data, the coefficient of distribution δ is calculated by the formula (6). Using Mathematica software package, a mathematical expression is compiled in a skilled form after the reduction of non-significant parts of the equation according to Student's criterion, which links the coefficient of distribution *δ* to the factors of research:

$$\delta = 67.568 - 4.87605\,D - 0.537449\,D^2 - 152.139\,Q - 1.22609\,V + 0.542871\,D\,V + 6.11275\,Q\,V - 0.0510141\,V^2 \quad (8)$$

The graphical interpretation of the dependence (8) is shown in Fig. 6. The optimum parameters of equation (8) under the condition of the maximum distribution coefficient δ are D_p = 3 mm, Q = 0.03 kg/s, V = 15 m/s. As it can be seen in Fig. 6, with increasing the seeds supply, the distribution factor θ decreases by parabola; the diameter of the seed D_p and the air velocity V affects the distribution coefficient δ by the function of the hyperbolic paraboloid.

The second stage, namely experimental research, has been carried out using the method of mathematical planning of the multifactorial experiment, which allows determining the mathematical processes' models in the form of regression equations. The obtained mathematical model of the influence of the investigated factors on the coefficient of distribution δ is the following:

$$\delta = 36.8588 - 0.87431\, x_1 + 0.0222222\, x_1^2 + 3.12163\, x_2 + 0.883579\, x_1 x_2 - 1.25313\, x_2^2 \qquad (9)$$

For this equation, the 95 % probability level of the dispersion is homogeneous, the value of the Cochran criterion G = 0.2594 <$G_{0.05}$ (2; 9) = 0.4755. Dispersion of the adequacy of the mathematical model S_{aad}^2 = 1.879; variance of experimental error S_y^2 = 1.4870; Fisher's value F = 1.26 <$F_{0.05}$ (5; 18) = 2.77. The model is adequate at any level of confidence probability. According to the calculated values of the correlation coefficients and Student's criterion $t_{0.05}$ (18) = 2.1, all coefficients are significant at the confidence level of over 95 %. In a sketched form, the model (9) has the following form:

$$\delta = 6.07089 - 29.1437\, Q + 2.62933\, V - 0.0501251\, V^2 \qquad (10)$$

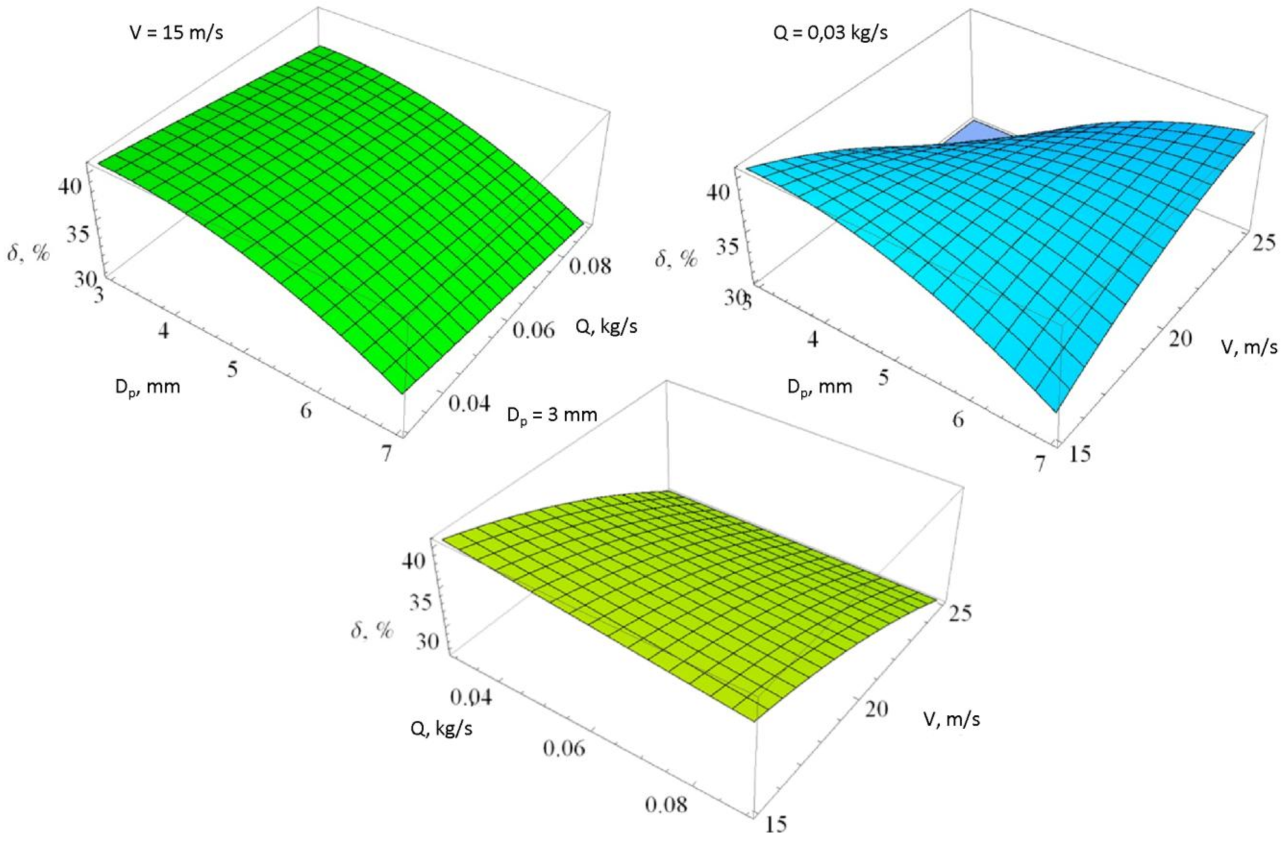


Fig. 6 – The dependence of the distribution coefficient δ on the effective diameter of the seed Dp, the seeding Q and the air flow velocity V

Analyzing equation (10), it can be argued that the factor of distribution δ is affected by all of the above-mentioned factors. At the same time, with increasing air flow velocity V, the distribution coefficient δ increases. And with increasing seed Q supply, the distribution coefficient δ decreases. The graphical interpretation of the experimental (10) and theoretical dependences (8) obtained at D_{p1} = 6 mm and D_{p2} = 7 mm is shown in Fig. 7. Statistical analysis showed that the correlation coefficient between the theoretical (8) and experimental (10) dependencies in the variation of the factors' values in the given range is 0.96.

The mathematical model of the influence of the investigated factors on the power consumed by the experimental installation, has the form:

$$P = 1.62667 + 0.0116667\, x_1 - 0.0183333\, x_1^2 + 0.995556\, x_2 - 0.000833333\, x_1 x_2 - 0.01\, x_2^2 \qquad (11)$$

For this equation, the 95 % probability level of the dispersion is homogeneous, the value of the Cochran criterion G = 0.1675 <$G_{0.05}$ (2; 9) = 0.4755. Dispersion of the adequacy of the mathematical model S_{aad}^2 = 0.00215; variance of experimental error S_y^2 = 0.00135; value of Fisher's criterion F = 1.59 < $F_{0.05}$ (7; 18) = 2.58; the model is adequate at any level of confidence probability. According to the calculated values of the correlation coefficients and Student's criterion $t_{0.05}$ (18) = 2.1, all coefficients are significant at the confidence level of over 95 %. In a sketched form, the model (11) has the form:

$$P = -2.35556 + 0.199111\ V \tag{12}$$

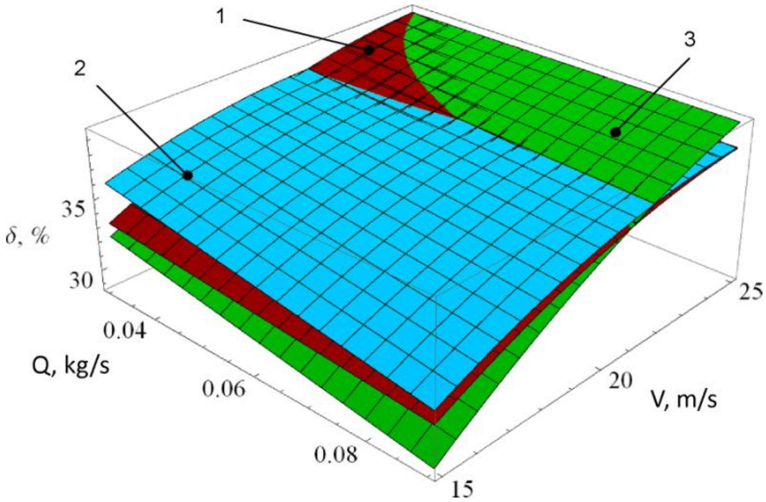


Fig. 7 – The dependence of the distribution coefficient δ on the seeds supply Q and air flow velocity V

1 – experimental dependence (10); 2 – theoretical dependence (8) with D_{p1} = 6 mm;
3 – theoretical dependence (8) with D_{p2} = 7 mm

The graphic interpretation of the obtained dependence (12) is presented in Fig. 8. Analyzing Equation (12), it can be argued that the power consumed by the experimental installation linearly affects only the air flow velocity V.

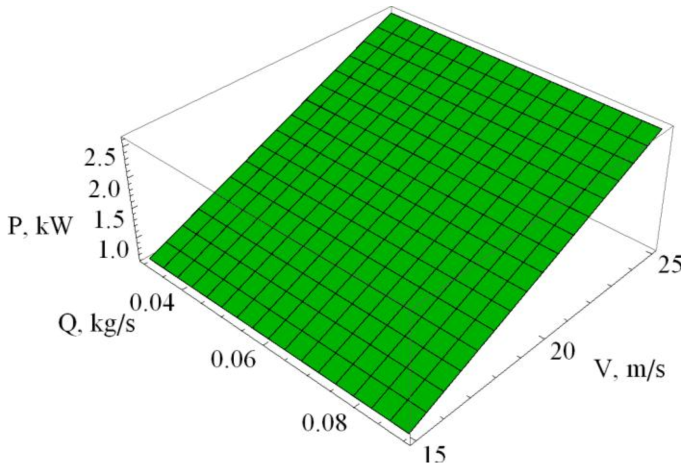


Fig. 8 – The dependence of the power P, consumed by the experimental installation, on the seeds supply Q and air velocity V

The task of solving a compromise problem was to minimize the power P consumed by the experimental installation, with the maximum value of the distribution coefficient δ and the seeds supply Q, that is:

$$\begin{cases} \delta(Q,V) \to \max, \\ P(Q,V) \to \min, \\ Q \to \max. \end{cases} \tag{13}$$

Convert the system of equations (13) to the form:

$$\frac{P(Q,V)}{Q\times\delta(Q,V)}\to\min. \tag{14}$$

The solution of the problem (14) with the aid of Mathematica software package leads to optimal technological regimes of the sunflower seeds separation during movement under the influence of air flow: Q = 0.09 kg/s, V = 15 m/s, δ = 31.6 %, P = 0.63 kW.

CONCLUSIONS

As a result of numerical simulation of the mechanical and technological process of sunflower seeds separation during movement under the influence of air flow, there has been developed the dependences of the distribution of each fraction of the seeds on the length of the area (average value, average square deviation σ, filling factor θ, distribution coefficient δ) from the seed effective diameter D_p, air flow velocity V and the seed supply Q. Under the condition of a maximum filling factor θ and a distribution coefficient δ, rational regime parameters of the specified process are defined: for effective diameter of the seed D_p = 5 mm supply is Q = 0.03 kg/s, and air velocity V = 15 m/s.

As a result of experimental studies of the mechanical and technological process of sunflower seed separation during its movement under the action of air flow, a physical-mathematical model was developed that linked the distribution coefficient δ and the consumed power P to the supply of seed Q and air velocity V. Statistical analysis has showed that the correlation coefficient between the theoretical and experimental dependencies in the variation of the factors' values in the given range is 0.96.

During the research, the compromise problem has been solved, in particular, the minimization of the power P consumed by the experimental installation with the maximum value of the distribution coefficient δ and the seeds supply Q: Q = 0.09 kg/s, V = 15 m/s, δ = 31.6 %, P = 0.63 kW.

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