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A DEVELOPING A MATHEMATICAL MODEL FOR SIMULATING THE SEEDS SEPARATION PROCESS ON THE PLANE SIEVES

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În lucrare se dezvoltă un model matematic privind procesul separării semințelor pe sitele plane prin utilizarea pentru prima dată a teoriei analizei dimensionale. Acest model permite anticiparea coefi cientului separării „semințelor mici” care evaluează eficiența procesului separării efectuat de sita plană. Având în vedere studiile teoretice şi experimentale anterioare, în lucrare s-au considerat în final un număr de 7 parametri principali care caracterizează procesul de separare. Pe baza teoremei Π (Buckingham) din teoria analizei dimensionale, s-au obținut criteriile de similitudine adimensionale şi s-a propus modelul matematic pentru coeficientul de separare sub forma produsului de puteri a criteriilor de similitudine, de tipul: $\varepsilon = k \cdot \left(q / n A^2 \rho_v\right)^{a_1} (l / A)^{a_2} c_i^{a_3}$.

Utilizând datele experimentale obținute pe o sită plană prevăzută pe o maşină existentă cu caracteristici constructive şi funcționale cunoscute, s-a testat valabilitatea relației propuse. S-au găsit valorile coeficienților: k = 5,528; a_1*= 0,395;* a_2*=0,303;* a_3*=0,381, pentru un coeficient de corelație* R^2*=0,855. Aceasta probează că modelul matematic propus poate fi utilizat la anticiparea acceptabilă a valorii coeficientului de separare a „semințelor mici” ale unei site plane, fiind util atât proiectanților, cât şi utilizatorilor din domeniul maşinilor pentru curățirea şi sortarea semințelor prevăzute cu site plane.*

In this paper, a mathematical model of separation of the seeds on plane sieves is developed by using for the first time the theory of the dimensional analysis. This model allows anticipating the coefficient of separation of the “small seeds”, which evaluates the efficiency of the separation performed by the plain sieve. Considering the theoretical studies and the previous experiments, 7 main parameters which characterise the process of separation have finally been taken into account. Based on the Π (Buckingham) theorem pertaining to the theory of dimensional analysis, the criteria of dimensionless similarity have been obtained and the mathematical model has been proposed for the coefficient of separation under the form of the powers multiplication of the similitude criteria, of the type $\varepsilon = k \cdot \left(q / n A^2 \rho_v\right)^{a_1} (l / A)^{a_2} c_i^{a_3}$.

Using the experimental data obtained on the plain sieve installed on an existing machine with known constructive and functional characteristics, the validity

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of the relationship proposed was tested. The values of the coefficients: k = 5,528; a_1= 0,395; a_2=0,303; a_3=0,381 were found for a coefficient of correlation R^2=0,855. This proves that the proposed mathematical model may be used when anticipating the corresponding separation coefficient values of the "small seeds" on a plane sieve, being useful for both planners and users in the field of the machines used for cleaning and sorting of the seeds, equipped with plane sieves.

Key words: cereal grains, cleaning process, plane sieve, dimensional analysis, mathematical model

1. Introduction and review

The operations of cleaning and sorting of the seeds are usually made by of the complex machines equipped with plain sieves. [4,11,19].

The process of cleaning of the seeds with the help of the plain sieves is essentially a process of separation which is based on the differentiation between the geometrical dimensions (width and/ or thickness) of the seeds, [4,5,11].

The seeds which have a smaller geometrical dimension than the dimensions of the holes are separated through the holes of the sieve, these seeds being called "small seeds", [3,4,19].

The process of separation is ensured by the relative vibratory move of the layer of fabric on the surface of the plain sieves, caused by their oscillatory movements.

The separation of the "small seeds" is made by their movement within the layer of seeds and their passage through the holes of the sieve, [5,10,11,19].

This process is extremely complex, being influenced by numerous factors, namely: the specific feed flow rate q (kg/m.s); the content of small seeds of the original material c_i(%); the physical characteristics of the material in granular condition (volumic mass, density of the seeds, internal friction, external friction, granulometric distribution, geometric shape of the seeds), the geometric shape, the dimensions and display of the holes on the sieve; the kinematic operating regime of the sieve, the sieve's angle of inclination, [3,4,5,10,11].

Numerous experimental researches have shown the influence of these factors on the process of separation by means of plain sieves with circular and rectangular holes. [3,4,5,10,11,19].

In these researches, the efficiency of the process of separation as made by the sieve was evaluated through the coefficient of separation of the "small seeds" defined by the ratio between the quantity of "small seeds" separated and the quantity of "small seeds" contained by the original material, [3,4,5,11,19].

In order to anticipate the coefficient of separation under various conditions of operation of the sieve, different mathematical models have been developed, either by the empirical approach [3,5] and the interpretation of the experimental data or by the stochastic approach of the phenomenon of separation due to its random character [1,4,10,11,19] or by analogy with the separation in the system of cleaning with the sieves from cereal harvesters, [9,13,16,17,18].

The disadvantage of these ways of approaching is given by the low degree of applicability of the tested mathematical models for which the values of the coefficients contained by those models depend on the experimental conditions, which are not always the same as the concrete correlations.

These disadvantages are greatly overcome by explaining the main parameters of the process of separation in the mathematical models elaborated, [2,14,15].

Such a model of the type of a logistical function with coefficients which are functions of multiple linear regression in which the main parameters of operation of the sieves are included, has been developed by the authors for the cleaning system of the cereals harvesters, [14].

During the same mission, the authors have developed for the first time a model which simulates the separation in the cleaning system of the harvesters based on the application of the theory of dimensional analysis, [2,15].

In this paper, it was developed, also for the first time, a mathematical model used for simulating the process of cleaning of the "small seeds" on plane sieves by using the theory of dimensional analysis. The proposed model was tested against the experimental data obtained when cleaning the wheat seeds on the plane sieve of a modern cleaning machine of the type Westrup UP 150-0604 (Germany) on different feed flow rates and for various contents of "small seeds". Finally, the utility of the mathematical models developed was shown.

2. Development of the mathematical model

From the previous theoretical and experimental researches regarding the process of separation of seeds with plane sieves have resulted the physical means to be considered in the study of this process, [1,3-6,9,11,14,16,19]. These are: the specific feed flow rate, q (kg/m·s); the content of "small seeds" of the original material, c_i (%); the length of the sieves, l (m); the bulk density of the seeds, ρ_v (kg/m^3); the coefficient of friction of the seeds with the sieve, μ; the oscillation frequency of the sieve, n (osc/s); the amplitude of the sieve's oscillation, A(m); the angle of inclination of the sieve on the horizontal, α(°); the gravitation acceleration, g (m/s^2). The efficiency of the separation is evaluated through the coefficient of separation of the "small seeds"ε(%), defined by the ratio between the quantity of "small seeds" effectively separated along the length l of the sieve and the quantity of "small seeds" contained in the original material. [3,4,5,11,19].

The implicit function, which describes dimensionally the process of separation, where all the terms are dimensionally homogenous, compared to the fundamental physical means in the SI, [8,12,20] is:

$$f(n, A, \rho_v, \varepsilon, q, c_i, l, g, \alpha, \mu) = 0 \quad (1)$$

Considering the determining quantities which is formed the group (n,A,q), and based on the Π Buckingham theorem, [8,12,20] we found the dimensionless complexes (the similitude criteria) of the process of separation on the sieves. The dimensionless quantities ε, c_i, α and μ [8,12] go in directly and l and A, having the same length dimension, their ratio (*l/A*) will be dimensionless. For the other two physical means q and g the appropriate dimensionless complexes will be elaborated, namely:

$$\pi_1 = \frac{q}{n^{x_1} A^{x_2} \rho_v^{x_3}} \text{ and } \pi_2 = \frac{g}{n^{x_1'} A^{x_2'} \rho_v^{x_3'}} \quad (2)$$

where the exponents: x_1, x_2, x_3 and x'_1, $'x'_2$, x'_3 will be determined from the condition that π_1 and π_2 are dimensionless, compared to the fundamental physical means: L(length); M (mass); T (time).

The dimensional matrix of the 5 quantities is formed, compared to the fundamental means L, M, T, [8,12], presented in the relationship (3):

	x_1	x_2	x_3		
	n	A	ρ_v	q	g
L	0	1	-3	-1	1
M	0	0	1	1	0
T	-1	0	0	-1	-2

(3)

In order for π_1 to be dimensionless, compared to the other 3 fundamental dimensions L, M, T, we use the dimensional matrix (3), and the following linear equation system results from it:

$$\begin{cases} x_2 - 3x_3 = -1 \\ x_3 = 1 \\ -x_1 = -1 \end{cases} \quad (4)$$

By solving the system (4) the solutions: x_1=1; x_2=2; x_3=1 are found.

So, the first dimensionless complex (similitude criterion) is:

$$\pi_1 = \frac{q}{nA^2 \rho_v} \quad (5)$$

Doing the same with π_2, the solutions: x'_1=2; x'_2=1; x'_3=0 are found.

So:

$$\pi_2 = \frac{g}{n^2 A} \quad (6)$$

With these dimensionless means, the criterial equation under implicit form is obtained, being:

$$\varphi\left(\frac{q}{nA^2\rho_v},\frac{g}{n^2A},\varepsilon,\frac{l}{A},c_i,\alpha,\mu\right)=0 \tag{7}$$

If the separation coefficient ε is to be looked for, then:

$$\varepsilon=\varphi_1\left(\frac{q}{nA^2\rho_v},\frac{g}{n^2A},\frac{l}{A},c_i,\alpha,\mu\right) \tag{8}$$

If the specific debit q is looked for, then:

$$\frac{q}{nA^2\rho_v}=\varphi_2\left(\frac{g}{n^2A},\varepsilon,\frac{l}{A},c_i,\alpha,\mu\right) \tag{9}$$

In a first approximation, equation (8) under explicit form, the mathematical model of the power multiplications of the other dimensionless means is proposed for the efficiency of the process of separation:

$$\varepsilon=k^*\left(\frac{q}{nA^2\rho_v}\right)^{a_1}\left(\frac{l}{A}\right)^{a_2}c_i^{a_3}\left(\frac{g}{n^2A}\right)^{a_4}\alpha^{a_5}\mu^{a_6} \tag{10}$$

where k^*, $a_1, a_2, \ldots a_6$ are constant coefficients, computed by non-linear regression based on experimental data.

In the relationship (10) the last 3 factors may be neglected in some conditions and thus the result is:

$$\varepsilon=k\left(\frac{q}{n\,A^2\rho_v}\right)^{a_1}\left(\frac{l}{A}\right)^{a_2}c_i^{a_3} \tag{11}$$

Using the experimental data in Microsoft Excel and MicroCall Origin version 6.0, the quantities have been computed by multiple linear regressions of the values of the coefficients k, a_1, a_2, a_3.

Before this operation, equation (11) was linearized by applying a logarithm:

$$\ln\varepsilon=\ln k+a_1\ln\left(\frac{q}{nA^2\rho_v}\right)+a_2\ln\left(\frac{l}{A}\right)+a_3\ln c_i \tag{12}$$

The equation (11) was tested against the experimental data obtained by separating the wheat seeds on the plane sieve of a Westrup (Germany) machine and it was satisfactory, the obtained coefficient of correlation being $R^2 = 0.855$.

Admitting that the relationship (11) is valid for a certain degree of extrapolation (knowing the values of the coefficients k, a_1, a_2, a_3), it can be useful when evaluating the specific debit q (working capacity machine's Q=B.q) for values of the other parameters which are imposed or known.

3. Materials and methods

The experiments have been performed on sieve with rectangular holes using the seeds cleaning and sorting machine of the type Westrup UP 150-0604 (Germania), at S.C Agricover SRL-Slobozia. During the experiment, wheat seeds of the type SW Maxi, harvest of 2008 have been used for 11.5% moisture content and bulk density ρ_V=750 kg/m^3, after being harvested by combine. Four contents of "small seeds" have been included in the original material, having c_i=2.37%; 5.35%; 9.7%; and 18.54%. For each of these values, the experiments have been performed for 4 feed flow rates, namely: 500 kg/h; 600kg/h; 750 kg/h and 800 kg/h for a sieve with a width of B = 250 mm. The 2400 mm long sieve with rectangular holes the width of which is of 1.85 mm, with which the machine is equipped has been used.

The "small seeds" broken through the holes of the sieve have been collected in a box installed under the sieve and divided along the length in 12 compartments, each of 200 mm in length.

The total duration of each experiment was of 50 seconds, the compartments have been installed in the order from 1 to 12. Out of the total duration, maximum 20 seconds represent the duration at the beginning and at the end of each experiment, when the separation occurs under transitory regime, and during approximately 30 seconds the separation occurs under stationary regime, this type of separation representing more than 60%. This proves that the data obtained through experiments may be considered as resulting from a process of separation occurred under stationary regime.

The specific feed flow rates used in the experiments were: q=0.555 kg/m.s; 0.666 kg/m.s; 0.833 kg/m.s and 0.888 kg/m.s corresponding to the flow rates values mentioned above for a width of the sieve of 250 mm. The quantities of seeds separated by means of the sieves used in the experiments and corresponding to these specific feed flow rates were: 6.944 kg; 8.333 kg; 10.416 kg and 11.111 kg. The quantities of seeds computed in the compartments of the box below the sieve at each experiment have been weighted with the electronic balance with a precision of 0,01 g. The sieve has an amplitude of the oscillation A=10 mm, an oscillation frequency n=335 osc/min (5.58 osc/s) and an angle of inclination from the horizontal α=2^o. The lamellar elastic suspension supports were vertical, fact that was in accordance with the direction of longitudinal oscillation of the sieve on the horizontal line.

Other details regarding the characteristics of the used material and of the sieve and the working methodology are presented in [6].

4. Results and discussions

For the performed experiments, the feed flow rates with seeds (4 values), the content of "small seeds" of the original material (4 values) and the length of the sieve (5 values) have been modified, the other parameters being related to the physical properties of the material and to the kinematics of the sieve.

The primary data and their significance regarding the quantities of small seeds separated along the length of the sieve, obtained during the experiments have been selected and systematically presented in table 1.

Table 1.

The separation mass „small seeds" values m(g) and a separation coefficient ε(%) for 5 sieve lengths values l(m), and different specific feed flow rate values la q(kg/m.s) and two coefficient values c_i(%) – from experimental data

Q (kg/h)	l (m) / q (kg/m.s)	1.6	1.8	2.0	2.2	2.4
c_i = 2.37(%)						
600	0.666	80.0	87.0	91.8	95.8	98.7
c_i = 5.35(%)						
500	0.555	194	202	206	209	211
600	0.666	293	303	312	318	322
750	0.833	332	346	356	365	372
800	0.888	398	414	428	438	446

Based on the data on table 1, the data shown in table 2 were obtained, representing the separation coefficients ε (%), for 5 different lengths of the sieve, according to the relationship (determined by definition expression), namely:

$$\varepsilon = \frac{10^4 \cdot m}{c_i\, q\, B\, t} \ (\%) \qquad (13)$$

where: m(g) is the quantity of "small seeds" separated by the sieve on length l; c_i (%) – the content of "small seeds" within the original material; q(kg/ms) – the sieve's specific feed flow rate; B(m) – the sieve's width used in the experiments (B = 0,25 m); t(s) – the duration of an experiment (t = 50 s).

For the values in table 2, the values for the dimensionless complexes π_1 (eq.5) and ratio (l/A), as mentioned in table 3, have been determined based on computations.

By replacing in the equation (12) the values of the dimensionless complexes in the table 3, a system of 25 linear equations with 4 unknowns (k, a_1, a_2, a_3) is obtained and solved through the analysis of multiple linear regression in the MicroCall Origin program, vers.6.0.

Table 2.

The coefficient separation values ε(%) (eq.14) for 5 sieve lengths values l(m), for different values q(kg/m.s) and two coefficient values c_i(%), corresponding of data by table 1

Q (kg/h)	q (kg/m.s) \ l (m)	1.6	1.8	2.0	2.2	2.4
c_i = 2.37(%)						
600	0.666	40.5	44.0	46.8	48.8	50.2
c_i = 5.35(%)						
500	0.555	52.2	54.4	55.4	56.3	56.8
600	0.666	65.7	68.0	70.0	71.3	72.2
750	0.833	59.6	62.1	63.9	65.5	66.7
800	0.888	67.0	69.7	72.0	73.7	75.0

Table 3.

Dimensionless complex Π_1 (eq.5) and ratio (l/A) for all sieve length values, for different specific feed flow rate values q(kg/m.s) and different separation coefficient ε(%) (for table 2 data)

c_i(%)	q(kg/m.s)	ε(%)	$\pi_1 = \frac{q}{n A^2 \rho_v}$	$\pi_2 = \frac{l}{A}$	c_i(%)	q(kg/m.s)	ε(%)	$\pi_1 = \frac{q}{n A^2 \rho_v}$	$\pi_2 = \frac{l}{A}$
2.37	0.666	40.5	1.591	160	5.35	0.833	59.6	1.990	160
		44.0		180			62.1		180
		46.8		200			63.9		200
		48.8		220			65.5		220
		50.2		240			66.8		240
5.35	0.555	52.2	1.326	160	5.35	0.888	67.0	2.122	160
		54.4		180			69.6		180
		55.5		200			72.0		200
		56.3		220			73.7		220
		56.8		240			75.0		240
5.35	0.666	65.7	1.591	160					
		68.0		180					
		70.0		200					
		71.3		220					
		72.2		240					

Thus, by using the computer PC Pentium V, the values of the constant value k and the exponents a_1, a_2, a_3: k=5.528; a_1=0.395; a_2=0.303; a_3= 0.381 have been found.

By using these values, the relationship (11), which shows the dependency of the coefficient of separation ε(%) in the sieve's operating process depending on the parameters taken into account will become:

$$\varepsilon = 5.528 \left(\frac{q}{n A^2 \rho_v} \right)^{0.395} \left(\frac{l}{A} \right)^{0.303} c_i^{0.381} \tag{14}$$

In this situation, the correlation coefficient is R^2=0.855, which shows an appropriate validity of the equation (14) for the prediction of the coefficient of separation ε(%) for a plane sieve with rectangular holes used for the cleaning of the wheat seeds.

Equation (14) can be used, with good results, in prediction of the feed flow rate Q(kg/h) supplied of the plane sieve, whose width is B(m) (Q=B·q), for another parameters values ε, l, n, A, c_i, ρ_v, than those who were used in experiments. Thus, through adequate processing of the equation (14) one gets:

$$\frac{q}{n \cdot A^2 \cdot \rho_v} = 1.318 \cdot 10^{-2} \varepsilon^{2.532} \left(\frac{l}{A}\right)^{-0.767} c_i^{-0.965} \qquad (15)$$

Equation (15) may be used with good results when predicting the specific seeds feed flow rate of the plane sieves with rectangular holes used for cleaning the wheat seeds if the values of the other parameters are to be imposed: ε, l, n, A, c_i, ρ_v, within the limit of the values used for experiments (see table 1).

Another useful parameter in qualitative evaluation of the sieve separation process, is the purity of clean seeds from the "small seeds" p(%) (defined through weight (%) of the cleaned seeds in final obtained product). On the basis of those three coefficients definition (p(%), ε(%), c_i(%)) is established the relation involved in purity evaluation of the obtained product, such as:

$$p = \frac{100 - c_i}{10^4 - \varepsilon c_i} \cdot 10^4 \ (\%) \qquad (16)$$

where: ε(%) is evaluated from equation (14).

In figure 1, are shown in 3D the variation curves of the dimensionless criteria for ε depending on the other dimensionless criteria for the 3 values of the coefficient c_i(%), corresponding to equation (14).

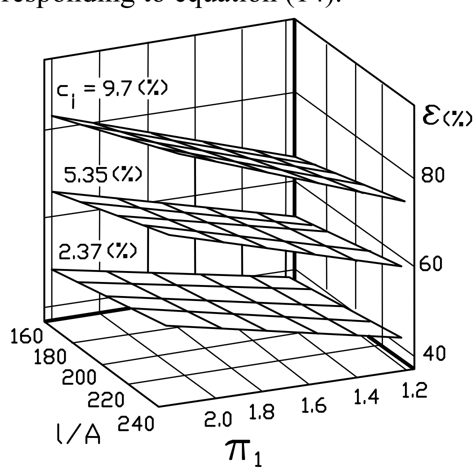

Fig.1. The variation curves of the separation coefficient ε(%) vs. different dimensionless criteria values π_1 and ratio (l/A) for three c_i(%) coefficient values, based eq.(14)

From the analysis of the curves in fig. 1, an increase of the separation coefficient ε by an increase of the specific feed flow rate of the seeds, q may be noticed.

Also, the values of ε and q evaluated by computation based on equations (14) and (15) for the data in table 2 have been compared to the values obtained by measurements, the differences were within the limits: -4.8% and +6.9% for ε and -5.1% and +6.5% for q, fact which proves the utility and applicability of equations (14) and (15).

From the testing of the mathematical models expressed in equation (11) for the process of separation of the seeds on plane sieves, it was possible to find a concordance with the data obtained by experiments, leading to equations (14) and (15), which are applicable to evaluations.

5. Conclusions

The use of the theory of dimension analysis for the mathematical modelling of the process of separation of seeds on plane sieves allowed finding the mathematical model to be used with good results, model of the type of equation (11), materialized by equations (14) and (15) for the prediction of the coefficient of separation of the "small seeds" ε(%) and of the specific seeds feed flow rate q of the sieve for known values of the main parameters of the sieve.

The mathematical models proposed have been tested against the experimental data and equation (15) was found for a coefficient of correlation R^2=0.855, thus proving the validity of the proposed mathematical model.

These equations ((14) and (15)) are important and allow a rapid estimate of the coefficient of separation of the "small seeds" ε(%) by the sieve, respectively of the purity of the product (eq. 16) and of the specific seeds feed flow rate q of the sieve, when the other parameters of the process of separation are known. They are particularly useful for the planners and users in the area of the post harvest machines of cleaning and sorting of the seeds, thus contributing to the enrichment of the database of this field.

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