

MATHEMATICAL MODELING OF EAR GRAIN SEPARATION PROCESS DEPENDING ON THE LENGTH OF THE AXIAL FLOW THRESHING APPARATUS

MODELAREA MATEMATICĂ A PROCESULUI DE SEPARARE A SEMINTELOR DIN SPICE, FUNCȚIE DE LUNGIMEA APARATULUI DE TREIER CU FLUX AXIAL

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ABSTRACT

Modelling the threshing and separation process involves the application of a method of description, analysis and analytical determination of system performance: threshing apparatus - working process. The modelling of the process of separating the seeds passing through an axial flow threshing device was performed taking into account that the separation function $s_s(x)$ is given depending on the length of the threshing apparatus. Then, models were made to describe the variation of the percentage (cumulative) of separated seeds $s_s(x=L)$, corresponding to the modification of the threshing apparatus functional parameters (depending on the peripheral speed of the rotor, the flow of straw parts and the moisture of straw parts).

REZUMAT

Modelarea procesului de treier și separare presupune aplicarea unei metode de descriere, analiză și determinare pe cale analitică a performanțelor sistemului: aparat de treier - proces de lucru. Modelarea procesului de separare a semințelor ce trec printr-un aparat de treier cu flux axial s-a realizat ținându-se cont că funcția de separare $s_s(x)$ este dată în funcție de lungimea aparatului de treier. În continuare s-au realizat modele care să descrie variația procentului (cumulat) de semințe separate $s_s(x=L)$, corespunzător modificării parametrilor funcționali ai aparatului de treier (în funcție de viteza periferică a rotorului, de debitul de părți păioase și de umiditatea părților păioase).

INTRODUCTION

The harvesting of straw cereals has been a major human activity throughout the history of civilization, and increasingly complex tools designed and made to facilitate this activity have given the process of creating them a significant place in all human activities (Ivan, 2014).

In general, the harvesting process of a cereal combine integrates the processes of harvesting, cutting, threshing, separation and cleaning, etc. (Hanna et al., 2013; Unakitan and Aydın, 2018). The threshing process represents an essential role in the operation of the combine, the seed losses occurring during harvesting being significantly influenced by the theory and technology of threshing (Ivan et al., 2015a; Ivan et al., 2015b; Fu et al., 2018; Khir et al., 2017). Natural losses are determined by weather conditions such as wind and rain (Audilakshmi et al., 2007; Gobbett et al., 2017). The degree of injury is another direct index of cereal threshing that negatively affects their market value and storage (Mirzazadeh et al., 2012; Khazaei et al., 2008) and depends on several factors, including the sieve separation regime (Pruteanu et al., 2018), the most common being the mechanical damage due to the impact of the seed kernel on the rigid surface of the threshing unit (Agelet et al., 2012; Zhu et al., 2016).

Modelling of the threshing and separation process emerged as a necessity to improve the quality of the threshing process. In the case of axial flow threshing apparatus, this was done later because of the fact that combines with longitudinal threshing apparatus appeared only after the 1970s. Shortly after this, the first researches in this field were made, continuing to this day when a sufficiently good modelling of the separation process has been reached (Li et al., 2017; Liang et al., 2017; Miu et al. al., 1997; Qirui et al., 2020; Sheychenko et al., 2018). This is also supported by the very good results obtained in operation with this type of threshing apparatus, the percentage of separated seeds often exceeding 99%. Experiments were performed in order to determine the constructive and functional characteristics of the combine based on a mathematical model of the displacement of the seed heap on the shaker (Ivan and Nedelcu, 2010).

The objective of this paper is to present a mathematical model that was made taking into account the input and output parameters of a working process carried out by an axial threshing apparatus.

MATERIALS AND METHODS

Input and output parameters of the system

The working process carried out by the threshing apparatus, regardless of its type, is very complex, being influenced by a series of parameters defined by:

- the material to be threshed;
- material feeding system of the threshing apparatus;
- its construction and working regime.

The mathematical model of the separation process developed in this paper takes into account the following input parameters:

- Material characteristics, represented by: seed moisture, u_s ; moisture of the straw parts, u_p ;
- Feeding system parameters: feeding width, l_a ; the height of the material layer when feeding takes place, h_a ; feeding speed, v_a ; feeding direction at angle γ ; material flow, q and the flow of straw parts, q_p .
- Construction of the threshing apparatus, characterized by: type: tangential or axial; beater (rotor) radius, R ; beater (rotor) length, L ; length of the concave's arc, l ; number of rails of the beater (rotor), z ; size on the radial direction of a rail, δ_R ; angle of the rails on the rotor to the generators, β_1 ; angle of the helical rails on the housing to the generators, β_2 .
- Operating regime, depending on: speed (angular speed, ω); peripheral speed of the beater (rotor), v ; beater (rotor) – concave (counter-rotor) spacing at the inlet δ_i ; beater (rotor) – concave (counter-rotor) spacing at the outlet δ_e .

Experimental installation and equipment used

The experimental researches performed on the axial flow threshing apparatus were carried out at INMA Bucharest on an axial flow thresher B-90 which is equipped with a threshing apparatus with a length of 2,000 mm. The thresher is actuated from the tractor's power take-off by means of a Cardan shaft which is coupled by a spring to the beater drive scutch.

The collection of the material heap separated by the concave was carried out using a matrix (10 x 5) of collecting boxes, a box having the dimensions: 200x200x100 [mm x mm x mm] (fig. 1).



Fig. 1 – Block of collecting boxes

Figure 2 shows a part of the constructive scheme of the experimental installation with axial flow threshing apparatus and Figure 3 a cross section of the threshing apparatus, under which the block of collecting boxes is mounted. Each line of boxes collects the material separated between two consecutive crossbars of the concave. The last line of boxes collects the heap separated in the transition area to the concave extension area.

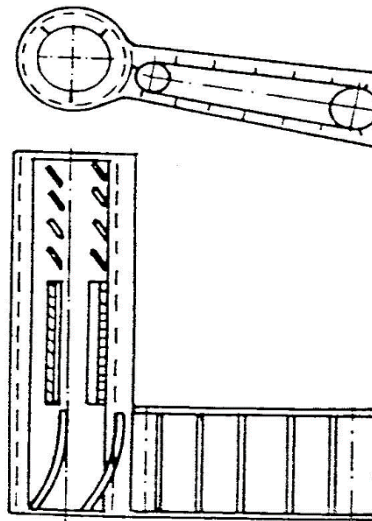


Fig. 2 - Constructive scheme of the experimental installation with axial threshing apparatus

The collection of the material evacuated at the outlet of the threshing apparatus (fragmented straw, unthreshed ears, unseparated seeds, chaff, etc.) was made on a tarpaulin with the dimensions of 2x3 sq. m, by means of two movable panels. Strain gauges were mounted on the beater shaft in order to measure the moment of resistance, by means of a specialized equipment.

The axial threshing apparatus has been fed tangentially in an area where the rotor is equipped with rails. In the same area, the housing of the threshing apparatus is provided with spiral rails, mounted at an angle of 60° to the axis of the rotor, which has a diameter of 560 mm. These rails are arranged on the housing, at an angle of 180° (Fig.2).

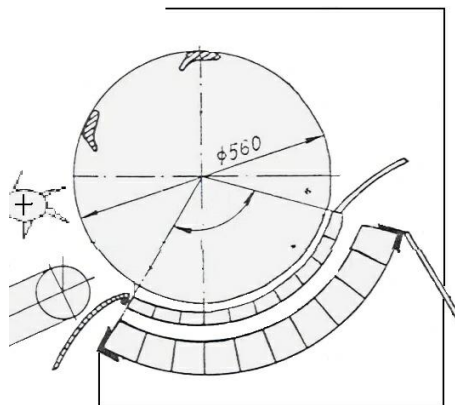


Fig. 3 – Cross section of the threshing apparatus

Figure 4 shows the constructive scheme of the axial flow threshing apparatus.

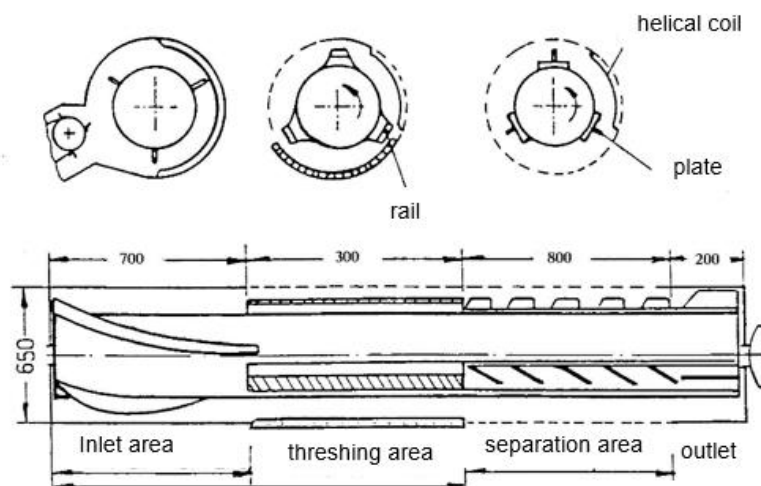


Fig. 4 – Constructive scheme of the axial flow threshing apparatus

The counter-rotor, with a winding angle of 110° has a construction similar to that of an ordinary tangential threshing apparatus, in the threshing area the rails are three in number and parallel to the rotor axis, in the separation area, on the same generators that the rails are mounted, the rotor being provided with three rows of separating plates, mounted inclined at an angle that can take the values of: 0° , 22.5° and 45° .

The housing of the threshing apparatus is provided entirely with holes measuring 20×40 mm, the active separating surface of the housing representing about 55% of its total surface. Helical rails 30 mm high and 500 mm long are mounted on the sides of the housing; they can be mounted at different angles: 60° ; 75° .

The main adjustable and measurable parameters taken into account, which influence the performance of the working process, were:

- beater speed n [rpm], adjustable within the limits of $600 \div 1200$ rpm; corresponding to this speed range, the peripheral speed of the beater being in the range $22 \div 32$ m/s;
- the material flow q [kg/s], was determined by weighing the sample of plant material and measuring the time in which the uniform feeding of the threshing apparatus was performed. The mass of material introduced into the apparatus was checked for each test with the mass of the components collected following the threshing process. During the tests the material flow corresponding to the width of the threshing apparatus was changed within the limits of $1.5 \div 4$ kg/s;
- the distance δ between the rails of the beater and the concave is variable, measured in the direction of material advance. Thus the distance δ can be varied as follows: $\delta_i = 12 \div 24$ mm at the inlet and $\delta_e = 3 \div 7$ mm at the outlet;
- the material feeding speed can be varied continuously by means of a speed variator, within the limits: $3.1 \div 4.65$ m/s;
- the material supply angle can vary within $15 \div 35^\circ$ and a clinometer is used to measure it.

Testing method

During the experiments, the values of several parameters were varied one by one, namely: the peripheral speed of the beater, the material flow, the S/PP ratio, the feeding speed, the distance between the beater and the concave.

The block of boxes for collecting the separated material is placed separately in the support guides on the chassis of the threshing apparatus module.

To collect the straw parts discharged, a tarpaulin and the movable panels for directing the material were properly placed so that it would not spread over the seeds.

The plant material required for the test was weighed and then placed on the feed conveyor belt, mainly with the ears positioned forward relative to the movement direction.

The thresher is put into operation by starting the tractor engine, the threshing apparatus being actuated from its power take-off, where the speed is checked and adjusted.

At the end of the experiment the material from the collecting boxes was then weighed separately as:

- separated seeds;
- unthreshed and separated seeds, namely seeds for the return circuit.

Samples were taken from the amount of separated seeds to determine the moisture of the seeds as well as to determine the percentage of damaged seeds.

The mass of material separated on the tarpaulin was weighed and recorded and then the block of collecting boxes was detached. The content of the 50 collecting boxes were placed in 50 numbered plastic or paper bags.

The material on the tarpaulin was processed manually, with great care, being separated in unthreshed ears (threshing loss), threshed and unseparated seeds (separation loss), discharged straw parts. A sample was taken from the discharged straw parts at each test to determine the moisture of the straw parts.

The separated material, from the 50 bags, was processed as follows: the material from each bag was separated after weighing into unthreshed but separated ears (seeds for the ear-return-spice circuit of the combine), separated seeds, separated straw parts. After manual separation of these components, the seeds separated in each collecting box were weighed with an electronic balance. Amounts of seeds were taken from the entire quantity of separated seeds, by the method of fractionation into quarters, to determine the moisture content of the seeds and to separate them into fractions of whole, broken and damaged seeds, which were weighed with the electronic balance.

The moisture of the seeds and the straw parts was determined by drying them in an oven at 105° .

RESULTS

The processing of the material separated in an experiment was done on the day of the experiment and during the following day. All data were entered in preliminary measurement tables.

Table 1

Den. no.	Separated seeds [g]					Sum
	A	B	C	D	E	
1.	12.4	23.4	27.5	16.5	4.9	84.7
2.	18.9	41.0	48.9	32.9	13.8	155.5
3.	23.3	43.9	51.1	33.9	12.4	164.6
4.	17.2	34.1	43.2	26.1	7.7	128.3
5.	16.6	34.6	39.5	29.5	8.1	128.3
6.	12.1	27.4	35.7	24.1	6.7	106.0
7.	10.4	22.2	27.2	24.6	6.4	90.8
8.	10.3	20.2	23.2	20.6	5.5	79.8
9.	7.6	16.2	23.7	15.2	3.8	66.5
10.	1.5	2.9	3.0	2.6	0.8	10.8
Sum	130.3	265.9	323.0	226	70.1	1015.3

The graphical representation of these data is shown in Figures 5-10.

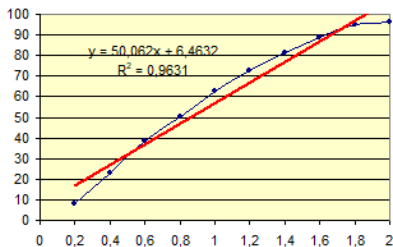


Fig. 5 - Linear function of seed separation

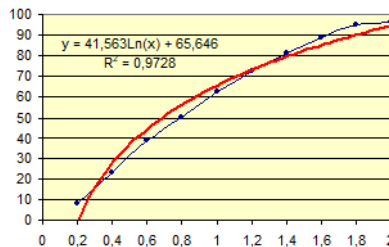


Fig. 6 - Logarithmic function of seed separation

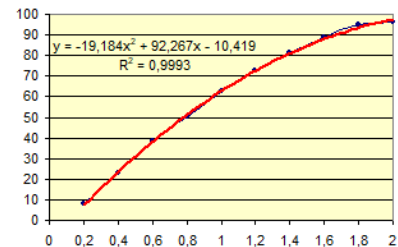


Fig. 7 – Second-degree polynomial function of seed separation

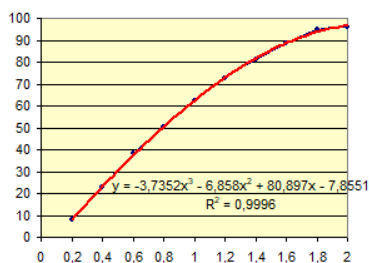


Fig. 8 – Third-degree polynomial function of seed separation

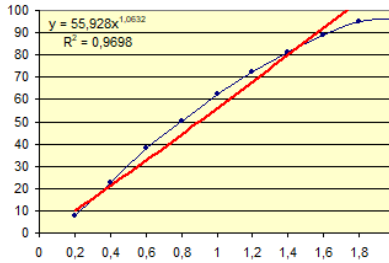


Fig. 9 - Power function of seed separation

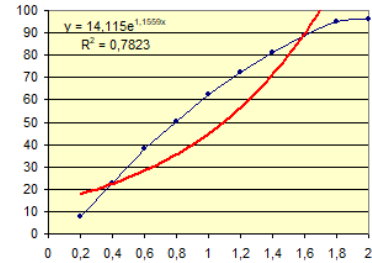


Fig. 10 - Exponential function of seed separation

— modelled function
— real function

Through the mathematical equations that compose it, the general mathematical model - in the case of the axial apparatus - describes mainly: the detachment of seeds from ears; separation of seeds by counter-rotor and housing; the size of losses at threshing and separation; separation of the straw parts.

On the length of the rotor $x \in (x \text{ takes the maximum value})$, the calculation expressions of the qualitative indices that characterize the threshing process of an axial device are obtained. The values of the coefficients β and λ used in this model, implicitly express the influences of all constructive, functional factors such as the physical and mechanical properties of the processed material.

Analysing the functions that model the separation process it can be observed that the polynomial functions of second and third degree best approximate the real function resulting from the data measured after performing the tests.

Thus, for *seed separation*, the second-degree polynomial function is of the form:

$$y = -ax^2 + bx - c \tag{1}$$

where: $a = 17.499 \div 26.752$;
 $b = 88.322 \div 104.87$;
 $c = 3.7228 \div 10.525$,

and the third-degree polynomial function is:

$$y = mx^3 - nx^2 + px - q \tag{2}$$

where: $m = -6.512 \div 3.7352$;
 $n = 6.858 \div 48.162$;
 $p = 80.897 \div 124.62$;
 $q = 5.5671 \div 10.488$.

The second-degree polynomial function approximates well the real function, the correlation coefficient varying between $0.9985 \div 0.9996$, while the third-degree polynomial function has a correlation coefficient between: $0.9991 \div 0.9998$.

Considering that the third-degree polynomial function approximates the real function better than the second-degree polynomial function with a maximum of 1.1 per thousand, it is considered that the second-degree polynomial function (1) approximates the real function well enough.

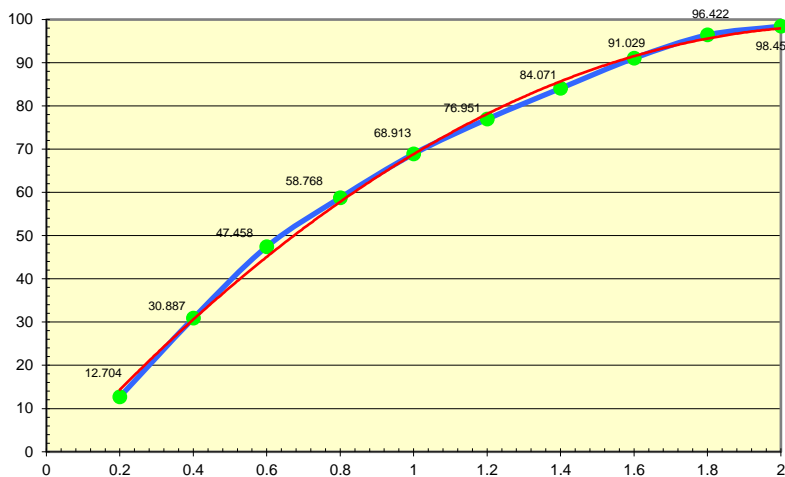


Fig. 11 – Seed separation depending on rotor length

In the case of this type of function, the range of values of a , b , and c is much narrower than in the case of the third-degree polynomial function, this highlighting the fact that the deviation from the real function is relatively small.

In the case of the axial apparatus, the separation of the seeds along the length of the threshing apparatus (threshing and separation areas) is described by:

- the cumulative frequency distribution function that quantifies the cumulative percentage of separated seeds for $x \in [0, L]$;
- seed separation density function that quantifies the frequency of seed separation over the length $x \in [0, L]$.

Next, models that describe the variation of the percentage (cumulative) of separated seeds $s_s(x = L)$, corresponding to the modification of the threshing apparatus functional parameters are proposed.

a) Seed separation depending on the peripheral speed of the rotor

The separation of seeds along the length of the axial threshing apparatus (threshing and separation areas) is described by a second-degree polynomial function of the form:

$$s_s(v_p) = -av_p^2 + bv_p - c \tag{3}$$

where: a , b , and c are experimentally determined values.

This function describes well the phenomenon of seed separation on the two areas (threshing and separation), taken separately or together.

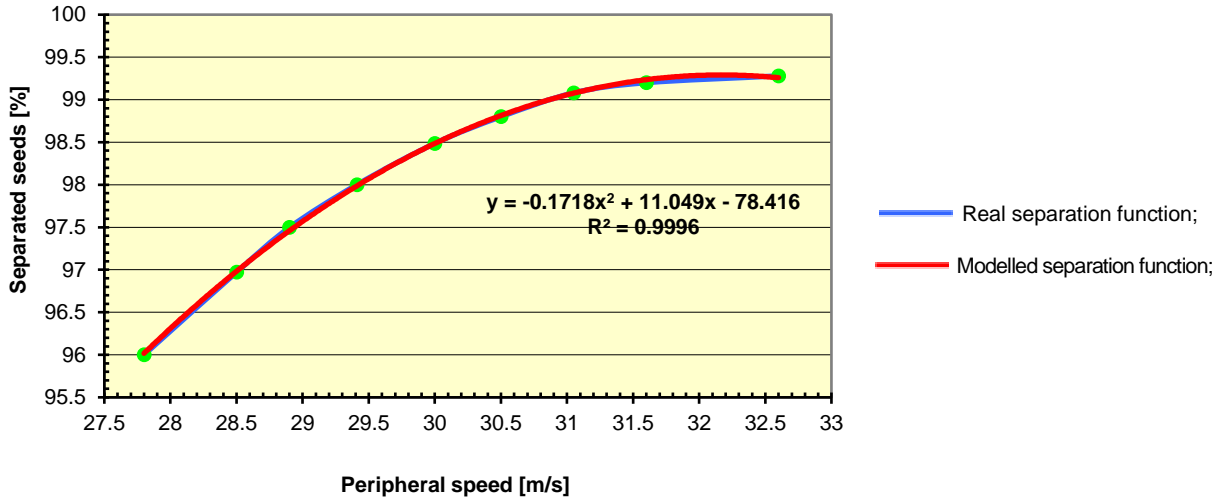


Fig. 12 – Seed separation depending on the peripheral speed of the rotor

The graph of this function (fig. 5) shows that at high peripheral speeds, the curves tend asymptotically towards a maximum separation of 100%.

It results that the dependence of the percentage of seeds separated by the peripheral speed of the rotor is described by a second-degree polynomial, whose maximum is obtained for:

$$v_p = \frac{b}{2c} \tag{4}$$

The detachment from the ears and the separation of the seeds through the counter-rotor and the housing take place due to the energy transmitted from the active elements (rails, plates, etc.) of the rotor, by impact. The higher the transmitted energy, the greater the separation of the seeds.

b) Seed separation depending on the flow of straw parts

In the case of the axial threshing apparatus tested for the variation of the flow of straw parts, there is a maximum of seed separation and with the increase of the flow of straw parts, the seed separation decreases continuously.

At low flow rates of straw parts, the distribution of the material in the space between the rotor and the housing is made in a thin layer, the material is more easily moved and therefore insufficiently processed; that is why the percentage of separated seeds decreases. At relatively high flow rates of straw parts, separation is hampered by the thick layer of material.

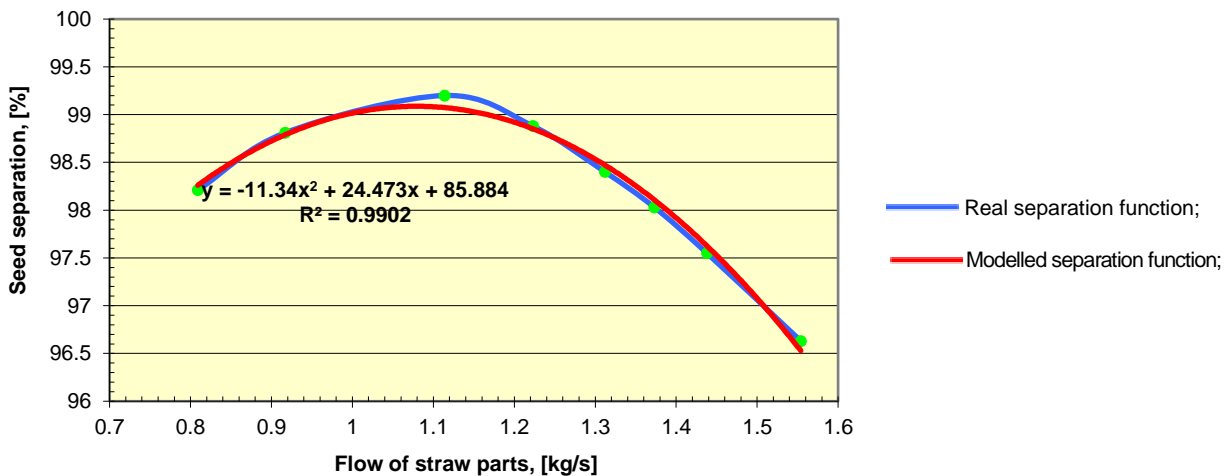


Fig. 13 – Seed separation depending on the flow of straw parts

$$s_s(q_p) = a + bq_p - cq_p^2 \tag{5}$$

where: a , b , and c are experimentally determined coefficients.

It results that the dependence of the percentage of seeds separated by the flow rate of straw parts is described by a second-degree polynomial, whose maximum is obtained for:

$$q_p = \frac{b}{2c} \tag{6}$$

c) Seed separation depending on straw parts moisture

Seed separation through the concave decreases with increasing the flow of straw parts almost linearly; at higher moisture, the percentage of separated seeds is higher. In the axial apparatus, seed losses (unseparated seeds) are higher when the material has a higher moisture content.

Data analysis suggests another way of interpreting the influence of moisture on seed separation. Due to the relatively long period of material remaining in the axial threshing apparatus, the moisture of the straw parts influences the separation of the seeds in two contradictory ways.

Thus, it can be said that at a low moisture of the straw parts, the detachment of the seeds is easy but the pronounced fragmentation of the straw prevents the separation of the seeds through the counter-rotor and the housing, which means that:

$$s_s = f(u_p) \tag{7}$$

where: u_p represents the moisture of the straw parts.

At a high moisture of the straw parts, threshing the material becomes more difficult, so

$$s_s = \frac{1}{f_2(u_p)} \tag{8}$$

A function that simultaneously describes the two modes of moisture influence can have the following form (fig. 7):

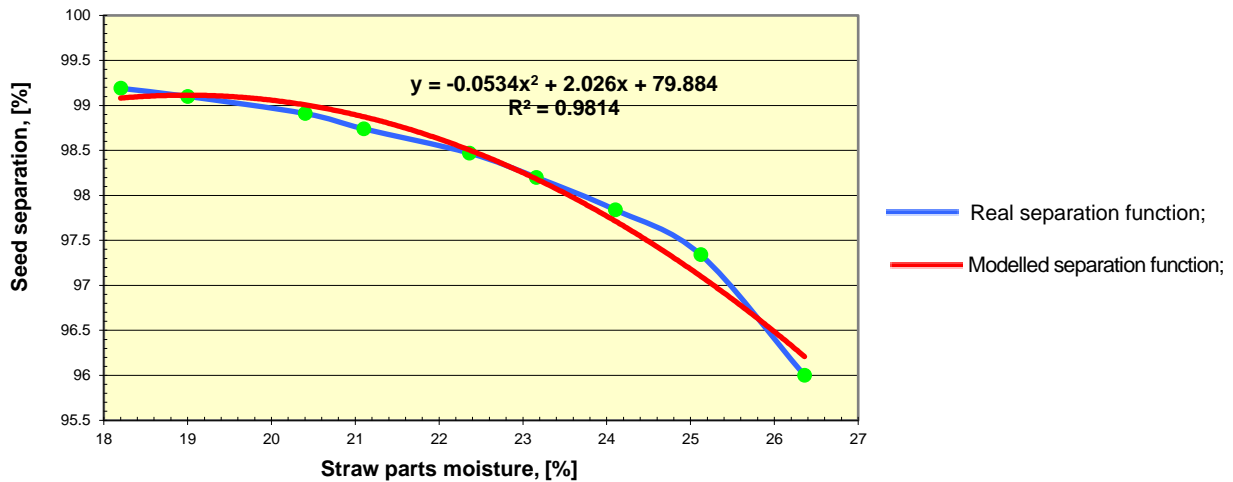


Fig. 14 – Seed separation depending on straw parts moisture

If:
$$\frac{ds_s}{du_p} = 0 \tag{9}$$

the value of the straw parts moisture for which the function (8) admits a maximum, respectively $u_p = \eta/\xi$, is obtained.

The function that best models the separation of seeds according to straw parts moisture also has a polynomial form of second-degree and is of the following form:

$$s_s(u_p) = -au_p^2 + bu_p + c \tag{10}$$

which has a maximum separation for:

$$u_p = \frac{b}{2c} \tag{11}$$

CONCLUSIONS

This paper presents a general mathematical model used to model the process of separating seeds from ears depending on the length of the threshing apparatus, seed separation being described by:

- the cumulative frequency distribution function for $x \in [0, L]$;
- seed separation density function over the length $x \in [0, L]$.

Then, models were proposed to describe the variation of the percentage of separated seeds $s_s(x)$, corresponding to the modification of the threshing apparatus functional parameters (seed separation depending on: peripheral speed of the rotor, the flow of straw parts and the moisture of straw parts).

Analysing the separation process, depending on these factors, the following observations can be distinguished:

- the separation of the seeds increases with the increase of the peripheral speed of the rotor, up to a limit speed of 32÷33 m/s; above this limit, the percentage of damaged seeds increases greatly;
- the separation of the seeds is done very well (reaches a maximum), for an average flow of the combine; at the limit (low or very high flow rates), the separation process is not performed satisfactorily;
- the moisture of the material entering the threshing apparatus and especially the moisture of the straw parts has a very big influence in the separation of the seeds; at a moisture higher than 18÷20%, the percentage of separated seeds begins to decrease.

To obtain these results, mathematical modelling was performed using the comparison of the results of the most used functions in the literature: linear, exponential, polynomial, power and logarithmic function, taking into account the function that best approximates the real separation function.

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