Метою теоретичних досліджень є підвищення ефективності технологічного процесу збирання насіння льону олійного жниваркою обчісуючого типу шляхом обґрунтування її конструктивно-режимних параметрів. Досягнення мети здійснено побудовою відповідної фізико-математичної моделі, що враховує технологічні параметри роботи комбайна і фізико-механічні властивості вороху льону олійного. Теоретичні дослідження були проведені шляхом чисельного моделювання в програмному пакеті STAR-CCM+. Фізико-математичний апарат базується на k–ε моделі турбулентності сполученої течії, моделі реального газу Ван-дер-Ваальса, осередненні по Рейнольдсу, рівнянні Нов'є-Стокса, моделі логранжевої багатофазності і моделі дискретних елементів.

Проведеними теоретичними дослідженнями встановлено вплив конструктивно-технологічних параметрів жниварки обчісуючого типу на якість протікання процесу в її області при збиранні льону олійного прямим комбайнуванням при обчісуванні рослин на корені. Доведено, що на протікання процесу суттєвий вплив має повітряний потік, що утворюється при роботі бітером-відбивачем і обчісуючим барабаном жниварки. У результаті чисельного моделювання процесу сепарації вороху льону олійного в жниварці обчісуючого типу встановлено розподіл потоку повітря в її області. Визначено залежності максимальної швидкості повітряного потоку від частоти обертання бітера-відбивача і обчісуючого барабану. Максимальна швидкість повітряного потоку, що становить V_{max}=30 м/с, зумовлена частотою обертання бітера-відбивача і обчісуючого барабану: n_1=n_2=800 об/хв. Обґрунтовано положення повітряної сітки та апроксимована форма кожуха. Отримані раціональні конструктивно-технологічні параметри жниварки, що зумовлюють підвищення якості протікання процесу сепарації вороху: частота обертання бітера-відбивача n_1=782 об/хв, частота обертання обчісуючого барабану n_2=671 об/хв, положення прозорої зони границь L=0,82 м і її ширина B=0,45 м. Отримані фізико-математичні моделі дають змогу спрямованого регулювання режимних параметрів жниварок обчісуючого типу для процесу збирання насіння льону олійного

Ключові слова: жниварка, технологія обчісування на корені, льон олійний, конструктивні параметри, повітряний потік, процес сепарації

UDC 631.17; 633.1
DOI: 10.15587/1729-4061.2019.169664

RESULTS OF NUMERICAL MODELING OF THE PROCESS OF HARVESTING THE SEEDS OF FLAX BY A HARVESTER OF THE STRIPPING TYPE

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1. Introduction

Harvesting is the main technological operation in the production of agricultural crops. Modern technologies imply a transition from the classic harvesting of cereals and other crops using a combine harvester to the most promising technology of plant stripping at the root. The effectiveness of such an approach means bringing down the energy consumption during harvesting process by reducing the load on the threshing-separating systems of combine harvesters, improving the quality indicators for harvesting, better performance, etc. [1, 2].

Designing effective technical means for harvesting crops, including flax, using a stripping method implies complex interactions and nonlinear relationships between the environment and devices' working bodies. That predetermines the complexity of mathematical modelling of the optimization and control processes.

Significant impact on the quality of the harvester's technological process is exerted by the formation of an air flow by a beat-reflector and stripping rotor, which varies in direction and magnitude. The proper formation of an air flow and the separation of pile in the region of a harvester of the stripping type could become a prerequisite for improving its efficiency in the technology of harvesting agricultural crops.

Given the significant effect exerted on the process of stripping by an air flow that forms in the region of a harvester, it is a relevant task to undertake a research aimed at the further improvement and design of technical equipment with high efficiency indicators. This can be achieved by substantiating the rational structural-technological parameters of stripping devices.

2. Literature review and problem statement

The current state of development of technical equipment for the harvesting of agricultural crops implies using a method of stripping the plants at the root. Given the scientific justification for the specified field of mechanical engineering, there are examples testifying to the efficiency of using products by leading manufacturers of single and two-rotor designs of harvesters [4–6]. Specifically, single-rotor stripping harvesters that are available in the market of harvesting machinery are made by the British company Shelbourne Reynolds [5] and the Russian company OAO «Penzmash» [6]. The two-rotor harvester «Slavyanka» is manufactured by the enterprise Ukr. Agro-service (Ukraine) [4].

The studies reported in [7–10] found that the significant effect on the quality indicators for the process of harvesting agricultural crops using a method of stripping is exerted by the structural-operational parameters of harvesters, as well as the parameters of related processes. The related processes, first of all, include the formation of an air flow in the region of a harvester at rotation of the rotor-reflector and the stripping rotor. Work [7] established that the magnitude of losses of grain at harvesting is affected by the position and frequency rotation of a stripping rotor, the translational speed of a machine, and the air flow velocity. In this case, the authors found that the air flow velocity at the inlet should be not less than 5 m/s and should reduce at the outlet in the region of an integrated auger. The authors established that the gap between a rotor and a casing of the device must be in the range from 0.09 to 0.11 m. It should be noted that the authors' recommended values for this indicator, based on the results obtained in [8], helped determine the distance between a rotor and a casing in the front part, which at radius of the stripping rotor of 0.35 m amounts to 0.14 m. In this case, according to the results of the study, they concluded about the feasibility of applying a suction air flow formed by a harvester's stripping rotor, thereby positively affecting quality of the process. The expediency of taking into consideration and formation of an air flow, which predetermines the ability to control the process has been proven in papers [9, 10]. According to authors of [9], enhancing the effectiveness of harvester operation necessitates ensuring the establishment of a motion mode of a pile's components considering their sail capacity. The work argues that it is an appropriate mode when the value for average speed of an unstripped pile's components would exceed the speed of grain. In this case, it was demonstrated by the mathematical model of the process of stripping agricultural crops, built in [9], that the air flow velocity, formed by a rotor, is included in the equation of grain motion along a stripping tooth and a transporting channel. To account for the influence of air flow velocity on the movement of grain, one must know its numerical value, as well as a direction, as was studied in [10]. The authors found that the process of transporting a stripped pile is accompanied by its partial segregation. One of the reasons of this phenomenon may be a process of layering of an air flow, detected in [11]. It is unclear how the authors accounted for the dimensional characteristics of the distance between a rotor and a casing of the device at the inlet to the channel and at the outlet.

In addition, the influence of the examined parameters on the shape formation of a harvester's casing was not substantiated, as well as the agreement between the current research results and results reported in earlier studies.

It is possible to improve efficiency of a harvester of the stripping type by introducing an additional beat-reflector to its design [12]. Such an approach has made it possible to reduce the loss of grain by up to 0.85...1.0 %. The authors found that the shape of the casing's front wall depends on the radius of the rotor, the position of its lower edge, and the angle of falling onto this surface. In this case, the motion of grain along the inner surface of the casing, for which they derived its curvature and which ensures a reduction in the magnitude of losses, was considered without accounting for the influence of an air flow formed in the region of a harvester. To enhance quality indicators in the operation of a two-rotor stripping device, [13] reported obtaining the optimal parameters for a beat-reflector. These parameters are: the diameter of a beat-reflector d=0.38 m and the frequency of its rotation ω=86.9 s^{-1}. That has made it possible to reduce the loss of grain at harvesting from 3.3 % to 1.6 %. In this case, the author failed to take into consideration, when modeling the process, the impact of an air flow formed in the region of a stripping harvester.

Thus, there is reason to believe that the lack of detailed research into the influence of an air flow in the region of a harvester of the stripping type on quality of the process of harvesting plants using a method of their stripping necessitates our study in this field.

3. The aim and objectives of the study

The aim of this study is to substantiate theoretically the structural-technological parameters for a harvester of the stripping type that is used to harvest flax. That would make it possible to build more effective technical tools for harvesting using a method of stripping plants at the root.

To accomplish the aim, the following tasks have been set:

– to determine the speed mode of an air flow in the region of a harvester of the stripping type and to substantiate the geometric shape of its casing, the size and position of an air grid;

– to explore the process of pile displacement in the region of a harvester of the stripping type with a curvilinear shape of the casing and to substantiate its structural-technological parameters.

4. Results of numerical simulation of the processes that occur in the region of a harvester of the stripping type

4. 1. Substantiation of structural parameters for a harvester

Determining a speed mode of air displacement in the region of a harvester of the stripping type would make it possible in the future to substantiate the geometrical shape of a harvester's casing, the size and position of an air grid depending on operational parameters of the stripping rotor and beat-reflector.

To obtain a vector field of velocities in the region of a harvester of the stripping type, we shall consider the process of air movement for a flat problem of numerical simulation in the *XOY* coordinates. The estimated scheme of a harvester of the stripping type is shown in Fig. 1.

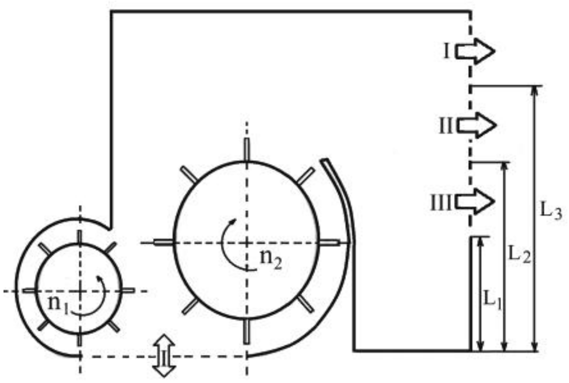


Fig. 1. Estimated scheme of a harvester of the stripping type

We calculated the air flow regimes in the region of a harvester of the stripping type under the following boundary conditions:

1. The boundaries represent the rigid walls that are not permeable to air flow. In this case, air velocity at their surface equals 0 m/s.

2. The region of boundary I is transparent with the predefined constant atmospheric pressure.

3. The regions of boundaries II–IV can be transparent with the predefined constant atmospheric pressure, or rigid walls, depending on the examined variant of a numerical experiment.

The beat-reflector rotates counterclockwise at frequency n_1, the stripping rotor – at rotation frequency n_2 (Fig. 1).

The air flow was investigated using the software suite *STAR-CCM+*, which is implemented based on a finite element method [14, 15]. In this case, we applied the adaptive regular computational grids with a variable size of the cell. The base size of a cell was adopted to be 0.001 m. The model of a grid chosen was the generator of a prismatic layer, the generator of polyhedral cells, and the generator of a surface grid. Results from numerical modeling of the flow of a real gas by van der Waals (air) greatly depend on the chosen model of turbulence, the choice of a computations grid, the number of its nodes, as well as the computing algorithm. That predetermined the verification aimed at ensuring the convergence of the results obtained. We have chosen the following physical models for numerical simulation: the k–ε conjugated flow turbulence model, the field of gravity force, the model of real gas by van der Waals, the Navier-Stokes equation averaged for Reynolds [16, 17].

To model numerically the process of air displacement in the region of a harvester of the stripping type, we selected the structural-technological parameters for a standard two-rotor harvester [18]. The following structural-technological parameters were chosen to be the factors in numerical modeling: the beat-reflector's rotation frequency n_1, the rotation frequency of stripping rotor n_2 and the position of a transparent zone of boundaries L. The limits of variation for the examined factors are given in Table 1.

Table 1

The levels of variation for the factors in numerical simulation

Factors' levels of variation	Factors		
	Rotation frequency of beat-reflector n_1, rpm	Rotation frequency of stripping rotor n_2, rpm	Position of transparent zone of boundary L, m
Upper level (+)	800	800	0,35
Basic level (0)	600	600	0,60
Lower level (–)	400	400	0,85
Interval of factor variations	200	200	0,25

Numerical modeling was carried out based on the full factorial experiment with a total number of experiments $3^3=27$. The modeling results were used to obtain the visualization of air flow velocity distribution in the region of a harvester of the stripping type (Fig. 2).

For each variant of the numerical experiment, we calculated the maximum air velocity using the software suite Wolfram Mathematica, and approximated the data obtained, the result of which is the established dependence on the examined factors in an encoded form:

$$V_{\max} = 21.1293 + 0.677778x_1 - 0.0177778x_1^2 + \\ + 1.72333x_2 + 0.1375x_1x_2 + \\ + 1.21222x_2^2 + 6.42111x_3 - 0.2125x_1x_2 - \\ - 1.8025x_2x_3 + 0.84556x_3^2. \quad (1)$$

The statistical treatment of the resulting equation (1) is summarized in Table 2; analyzing the results makes it possible to reduce nonessential coefficients in equation (1) and record it in the following form:

$$V_{\max} = 21.1293 + 1.72333x_2 + 1.21222x_2^2 + 6.42111x_3 - \\ - 0.2125x_1x_3 - 1.8025x_2x_3 + 0.845556x_3^2. \quad (2)$$

Following the transformation of equation (2) into the decoded form, we obtain:

$$V_{\max} = -2.53657 + 2.55L - 0.0007125n_1 + \\ + 0.0000303056n_1^2 + 0.0363264n_2 - 0.00425Ln_2 - \\ - 0.00425Ln_2 - 0.0000450625n_1n_2 + 0.000021389n_2^2. \quad (3)$$

By registering, in turn, the factors of experiments at a certain level, we built the graphic interpretations of dependence (3), shown in Fig. 3.

Fig. 3 shows that increasing the rotation frequency of a rotor-reflector n_1 and stripping rotor n_2 increases the maximum air velocity in the region of a harvester $V_{\max}$ governed by a parabolic law. In turn, the position of a transparent zone of boundaries L almost does not affect the value for a maximum air velocity $V_{\max}$, and, according to Fig. 2, characterizes its direction only.

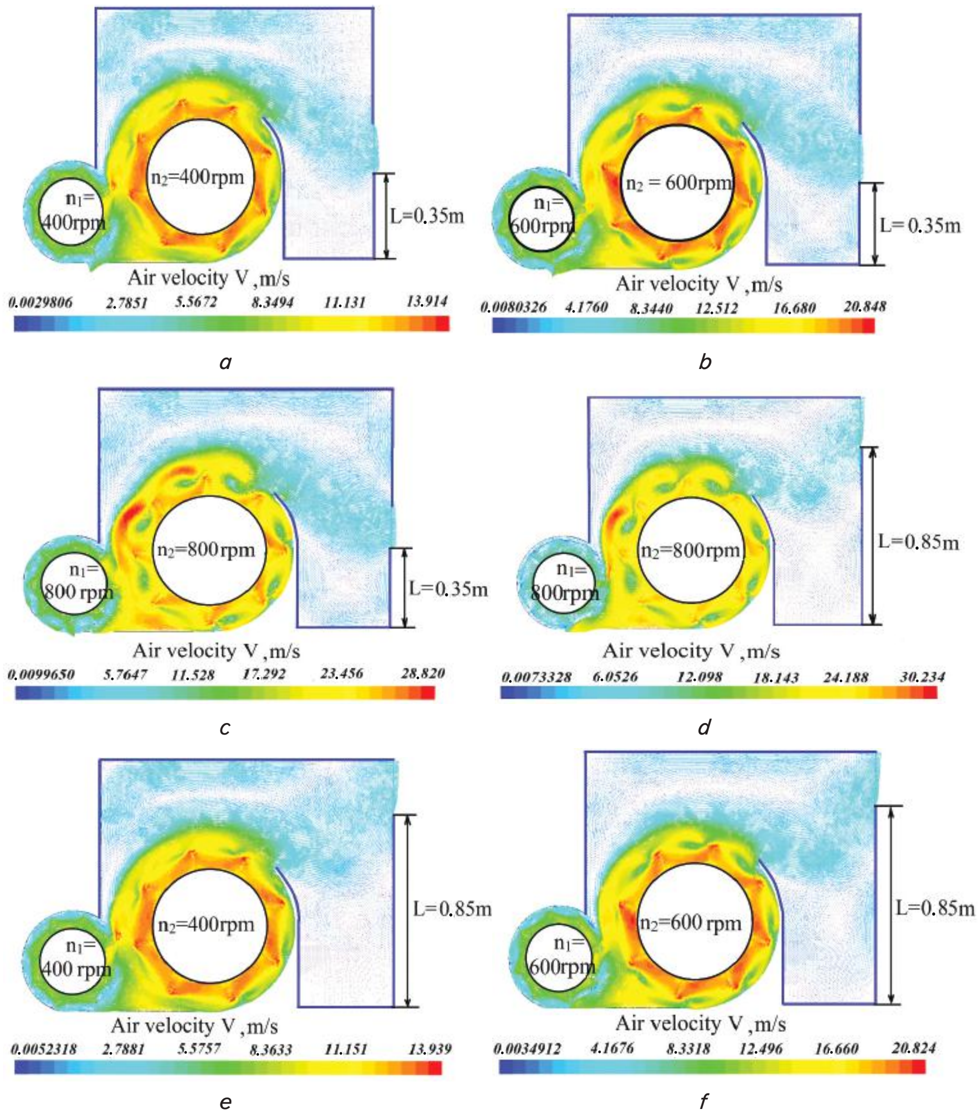


Fig. 2. Visualization of air flow velocity distribution in the region of a harvester of the stripping type at the following parameters values: *a* — $n_1=n_2=400$ rpm, $L=0.35$ m; *b* — $n_1=n_2=600$ rpm, $L=0.35$ m; *c* — $n_1=n_2=800$ rpm, $L=0.35$ m; *d* — $n_1=n_2=600$ rpm, $L=0.85$ m; *e* — $n_1=n_2=400$ rpm, $L=0.85$ m; *f* — $n_1=n_2=800$ rpm, $L=0.85$ m

Table 2

Statistical treatment of equation (1)

Coefficient*	s_i**	$t_{sc}s_i$***
a_0	0.636742	33.1834
a_{10}	0.294754	0.229947
a_{20}	0.294754	5.84668
a_{30}	0.294754	21.7846
a_{12}	0.360999	0.380888
a_{13}	0.360999	–0.588645
a_{23}	0.360999	–4.99309
a_{11}	0.510529	–0.0348223
a_{22}	0.510529	2.37444
a_{33}	0.510529	1.65623

*Notes: * – coefficients of equation* $y(x_1, x_2, x_3)=a_0+a_{10}x_1+a_{11}x_1^2+a_{12}x_1x_2+a_{13}x_1x_3+a_{20}x_2+a_{22}x_2^2+a_{23}x_2x_3+a_{30}x_3+a_{33}x_3^2$; *** – root mean square deviation, determined by comparing experimental data to the calculated equation* $y(x_1, x_2, x_3)$; **** – t_{sc} – Student criterion*

According to Fig. 2, air velocity changes, depending on the operational parameters for a stripping rotor and a beat-reflector, from 0 to 30 m/s.

Based on studies into the aerodynamic properties of a flax pile's components, the speed of their deposition exceeds 2 m/s.

Thus, the air velocity from 0 to 2 m/s does not affect the movement of the components. Imposing the velocity of an air flow in the region of a harvester of the stripping type in the range from 0 m/s to 2 m/s makes it possible to observe its boundary region where one registers the speed of 0 m/s (Fig. 4).

Approximating the boundary zone of a zero-air velocity in the region of a harvester of the stripping type in the form of a semicircle with radius $R_h=0.53$ m and a center $y_h=y_c=0.28$ m and $x_h=x_c=\Delta x_h=0.64$ m, we obtain the shape for a harvester's casing.

Using the software suite STAR-CCM+, we mapped the distribution of velocities of the formed air flow in the region of a harvester of the stripping type with the obtained shape of a casing that is shown in Fig. 5.

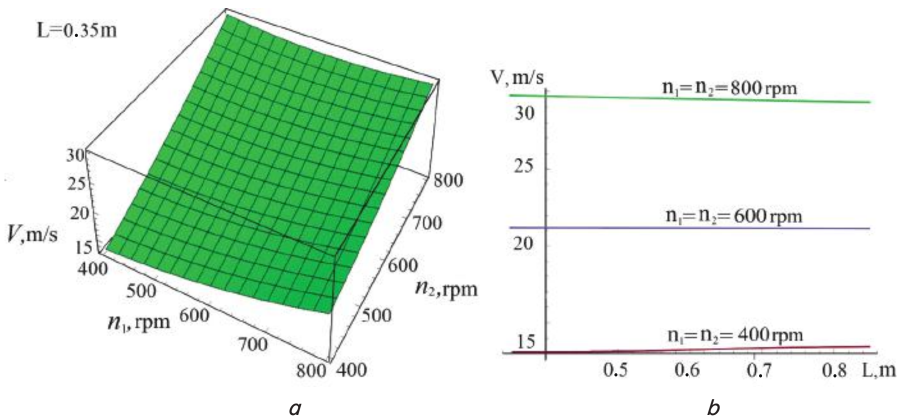


Fig. 3. Dependence of maximum air velocity on the experimental factors: *a* – rotation frequency of rotor-reflector and stripping rotor; *b* – position of a transparent zone of boundaries

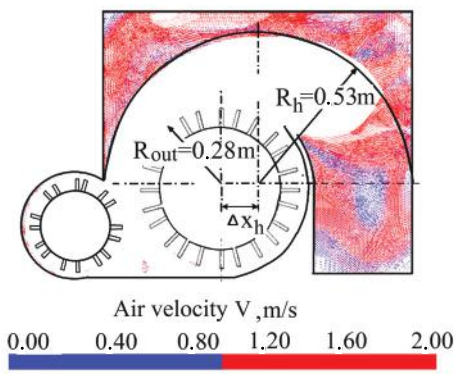


Fig. 4. A boundary zone of air zero velocity in the region of a harvester of the stripping type

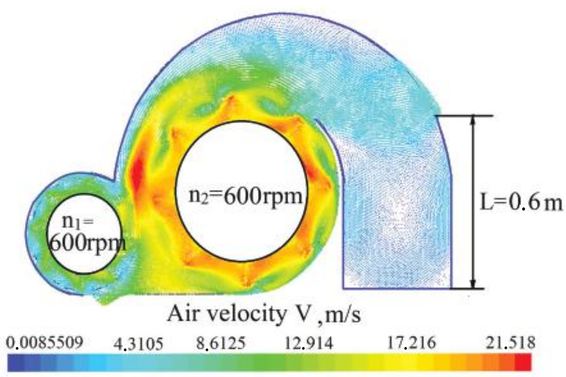


Fig. 5. Visualization of the distribution of air flow velocities in the region of a harvester of the stripping type with a curvilinear shape of the harvester's casing

Based on the results from numerical simulation of the aerodynamic processes in a harvester of the stripping type, we established the distribution of air flow velocities in its region. We have determined the dependence of maximum air velocity on the rotation frequency of beat-reflector n_1 and stripping rotor n_2 and the position of a transparent zone of boundary L. The approximated shape of the casing of a harvester of the stripping type takes the form of a semicircle with radius R_h=0.53 m and a center $y_h=y_c$=0.28 m and $x_h=x_c=\Delta x_h$=0.64 m.

4. 2. Substantiation of operational parameters for a harvester

To investigate the process of displacing components of a stripped pile in the region of a harvester of the stripping type with a curvilinear shape of its casing and in order to substantiate its structural-technological parameters, we performed numerical simulation using the software suite STAR-CCM+. The following physical models were employed: the k–ε model of conjugate turbulence flow, the field of gravity force, the van der Waals model of real gas, the Navier-Stokes equation averaged for Reynolds; a Lagrangian multiphase model, and a discrete element model.

Simulation of feeding the material was carried out in the zone of a stripping comb of the rotor. The initial orientation of all pile's components in space is random, and the initial motion speed of a stripped pile's components equaled 0 m/s. Based on data from our review of the scientific literature and earlier laboratory studies, we accepted the following physical-mechanical properties of a stripped pile's components whose values are given in Table 3.

Table 3

Physical-mechanical properties of pile components

Properties	Seed	Boxes with seed	Box husk	Stem segments
Volumetric mass, kg/m^3	710	90	60	30
Young modulus of elasticity, MPa	0.2	0.3	0.1	0.1
Poisson ratio	0.5	0.8	0.6	0.5
Mass share in a pile, %	40	10	40	10

The estimation scheme of a harvester of the stripping type with a curvilinear shape of its casing is shown in Fig. 6. Region I is transparent for all pile components (seeds, boxes of seeds, box husks, segments of the stem). Region II can be penetrated only by box husks, which is predetermined by the presence of an air grid with a diameter of round holes of 1.5 mm.

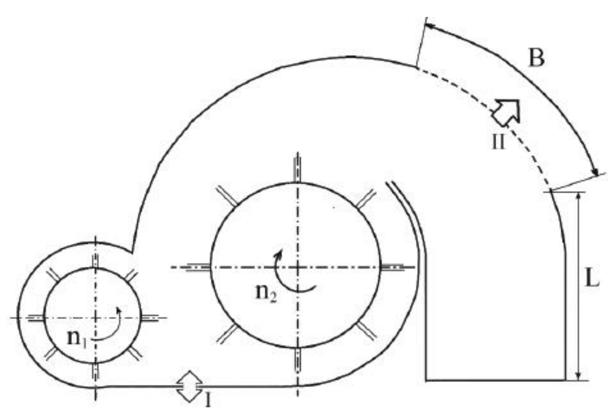


Fig. 6. Estimated scheme of a harvester of the stripping type with a curvilinear shape of its casing

The numerical modeling factors were the following structural-technological parameters: the rotation frequency of a beat-reflector n_1, the rotation frequency of a stripping rotor n_2, the position of a transparent zone of boundaries L, and its width B (variation range is given in Table 4).

The numerical modeling was conducted based on a full factorial experiment with a total number of experiments of $3^4=81$.

Table 4

Levels of variation for factors of numerical modeling

Levels of variation for factors	Factors			
	Rotation frequency of beat-reflector n_1, rpm (x_1)	Rotation frequency of stripping rotor n_2, rpm (x_2)	Position of transparent zone of boundary L, m (x_3)	Width of transparent zone of boundaries B, m (x_4)
Upper level (+)	800	800	0.35	0.45
Basic level (0)	600	600	0.60	0.30
Lower level (–)	400	400	0.85	0.15
Interval of factor variation	200	200	0.25	0.15

The criteria for estimating the process of pile separation in a harvester are: the mass fraction of the yield of husk and segments of the stem Δ_h, the mass fraction of the yield of seeds and boxes with seeds bolls Δ_s. We calculated the indicators based on formulae:

$$\delta_h = 100\left(1 - m_h/m_{hs}\right), \qquad (4)$$

$$\delta_s = 100\left(1 - m_s/m_{hs}\right), \qquad (5)$$

where m_h is the mass of husks and segments of the stem in the region of a harvester, kg; m_s is the mass of seeds and boxes of seeds in the region of a harvester, kg; m_{hs} is the mass of a pile, kg.

The result of modeling is the visualization of distribution of a pile's components in the region of a harvester of the stripping type (Fig. 7).

For each variant of a numerical experiment, we calculated the mass share of the yield of husk and segments of the stem from the region of a harvester Δ_h. By using the software suite Wolfram Mathematica, we approximated the data obtained and established the dependence on experimental factors in an encoded form:

$$\begin{aligned}\delta_h &= 33.8704 + 0.687037x_1 + 0.605556x_1^2 - \\ &- 2.87407x_2 - 0.236111x_1x_2 - 1.16667x_2^2 + \\ &+ 3.87222x_3 + 0.216667x_1x_3 + 0.108333x_2x_3 - \\ &- 0.172222x_3^2 + 5.40926x_4 - 0.125x_1x_4 - \\ &- 0.811111x_2x_4 + 0.0194444x_3x_4 + 0.15x_4^2. \end{aligned} \qquad (6)$$

The statistical treatment of the resulting equation (6) is given in Table 5; analyzing the data makes it possible to reduce nonessential coefficients in equation (6) and represent it in an encoded form:

$$\begin{aligned}\delta_h &= 9.47596 + 50.784B + 6.66667B^2 + 14.8956L - \\ &- 2.75556L^2 - 0.0125398n_1 - 0.00416667Bn_1 + \\ &+ 0.00433333Ln_1 + 0.0000151389n_1^2 + 0.0309824n_2 - \\ &- 0.027037Bn_2 + 0.00216667Ln_2 - 5.90278\cdot10^{-6}n_1n_2 - \\ &- 0.0000291667n_2^2. \end{aligned} \qquad (7)$$

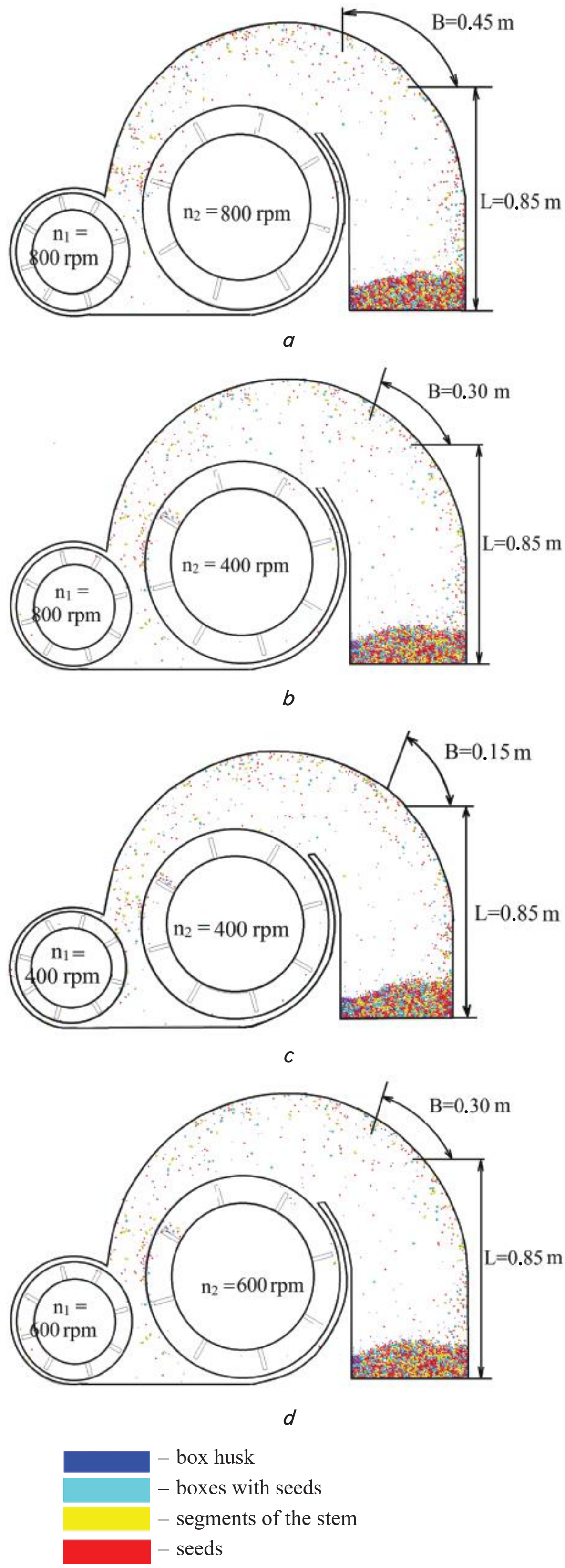


Fig. 7. Visualization of the distribution of a pile's components in the region of a harvester of the stripping type at the following parameter values: *a* – $n_1=n_2=800$ rpm, $L=0{,}85$ m, $B=0{,}45$ m; *b* – $n_1=800$, $n_2=400$ rpm, $L=0{,}85$ m, $B=0{,}30$ m; *c* – $n_1=n_2=400$ rpm, $L=0{,}85$ m, $B=0{,}15$ m; *d* – $n_1=n_2=600$ rpm, $L=0{,}85$ m, $B=0{,}30$ m

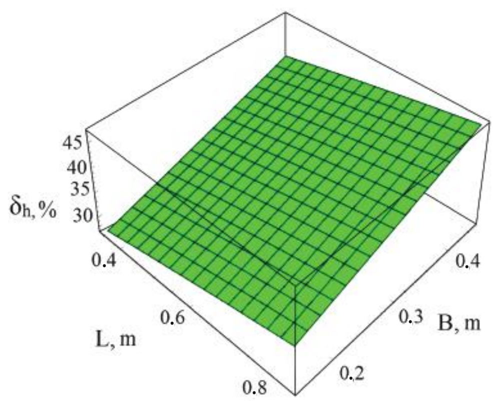
Table 5 gives the same notation as Table 2.

By registering, in turn, the experimental factors at a certain level, we built graphical interpretations of dependence (7) that are shown in Fig. 8.

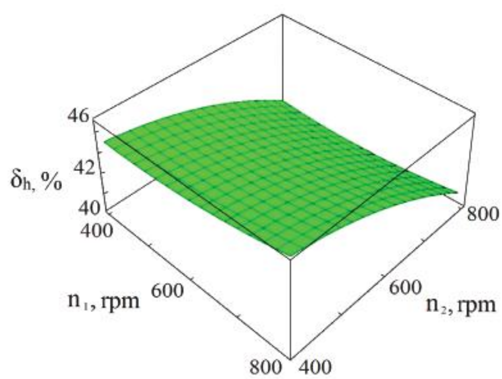
Table 5

Statistical treatment of equation (6)

Coefficient	s_i	$t_{sc}s_i$
a_{00}	0.855337	39.5989
a_{10}	0.34919	1.96752
a_{20}	0.34919	–8.23069
a_{30}	0.34919	11.0892
a_{40}	0.34919	15.4909
a_{12}	0.427668	–0.552089
a_{13}	0.427668	0.506623
a_{14}	0.427668	–0.292282
a_{23}	0.427668	0.253311
a_{24}	0.427668	–1.89659
a_{34}	0.427668	0.0454662
a_{11}	0.604815	1.00123
a_{22}	0.604815	–1.92897
a_{33}	0.604815	–0.284752
a_{44}	0.604815	0.24801



a



b

Fig. 8. Dependence of mass share of the yield from the region of a harvester Δ_h on experimental factors: *a* – rotation frequency of a rotor-reflector n_1 and stripping rotor n_2; *b* – position of a transparent zone of boundaries *L* and *B*

For each variant of the numerical experiment, we calculated the mass share of the yield of seeds and boxes with seeds from the region of a harvester Δ_h. By using the software suite Wolfram Mathematica, we approximated the data obtained, the result being the established dependence on experimental factors in an encoded form:

$$\delta_s = 4.09892 - 1.23483x_1 + 0.755854x_1^2 - 4.39665x_2 + 0.167115x_1x_2 + 5.4008x_2^2 + 0.266667x_3 + 0.0638889x_1x_3 + 0.00555556x_2x_3 + 0.337037x_3^2 + 0.275627x_4 - 0.752957x_1x_4 - 0.836738x_2x_4 - 0.0138889x_3x_4 + 0.212664x_4^2. \quad (8)$$

The statistical treatment of the resulting equation (8) is given in Table 6.

Analysis of data from Table 6 makes it possible to reduce the nonessential factors in equation (8) and represent it in a decoded form:

$$\delta_s = 68.4187 + 33.6314B - 5.40444L + 5.39259L_2 - 0.0213202n_1 - 0.0250986Bn_1 + 0.0000188964n_1^2 - 0.178318n_2 - 0.0278913Bn_2 + 0.000137252n_2^2. \quad (9)$$

Table 6 gives the same notation as Table 2.

Table 6

Statistical analysis of equation (9)

Coefficient	s_i	$t_{sc}s_i$
a_{00}	0.600928	6.82099
a_{10}	0.245328	–5.03337
a_{20}	0.245328	–17.9215
a_{30}	0.245328	1.08698
a_{40}	0.245328	1.1235
a_{12}	0.300464	0.556188
a_{13}	0.300464	0.212634
a_{14}	0.300464	–2.50598
a_{23}	0.300464	0.0184899
a_{24}	0.300464	–2.78482
a_{34}	0.300464	–0.0462248
a_{11}	0.424921	1.77881
a_{22}	0.424921	12.9203
a_{33}	0.424921	0.793177
a_{44}	0.424921	0.50048

By registering, in turn, the experimental factors at a certain level, we built graphical interpretations of dependence (9) that are shown in Fig. 9.

Fig. 9 shows that increasing the rotation frequency n_1 and the width of a transparent zone of boundaries *B* decreases the mass fraction of yield Δ_s. In turn, for rotation frequency n_2 and the position of a transparent zone of boundaries *L* there is an optimum (n_2=695 rpm, *L*=0.5 m) at which the mass fraction of yield Δ_s is minimal within the predefined range of factors.

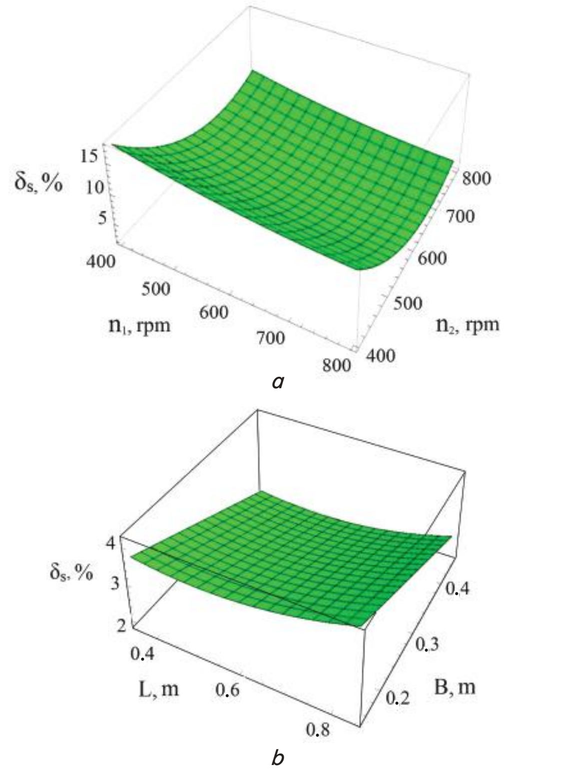


Fig. 9. Dependence of the mass share of the yield from the region of a harvester Δ_s on experimental factors: *a* – rotation frequency of a rotor-reflector n_1 and stripping rotor n_2; *b* – position of a transparent zone of boundaries *L* and *B*

To determine the rational structural-technological parameters for a harvester of the stripping type, we shall solve a compromise problem. The problem comes down to minimizing the mass share of the yield of husks and segments of the stem from the region of a harvester Δ_h and to maximizing the share of yield of seeds and boxes with seeds from the region of a harvester Δ_h. The result of the calculation is the derived rational structural-technological parameters of a harvester of the stripping type with a curvilinear shape of its casing. These parameters are: the rotation frequency of a beat-reflector n_1=782 rpm, the rotation frequency of a stripping rotor n_2=671 rpm, the position of a transparent zone of boundaries L=0.82 m and its width B=0.45 m.

5. Discussion of results of modeling the processes of a harvester of the stripping type for harvesting flax

Determining the influence of operational parameters for a beat-reflector and a stripping rotor on the velocity mode of air displacement in the region of a harvester of the stripping type follows from the obtained results (Fig. 2, 3). That makes it possible to change the configuration of a stripping chamber and necessitates the optimization of parameters for a stripping device in order to ensure the rational direction of pile motion.

It should be noted that increasing the rotation frequency of a beat-reflector and a stripping rotor predetermines an increase in the maximum speed of air flow Vmax in the region of a harvester in line with a parabolic law (Fig. 3). And under a slight impact from the indicator for a position of a transparent zone of boundaries *L*, which specifies only the direction of an air flow.

It might seem obvious that such a mechanism of the influence of operational parameters for a stripping device on the formation of an air flow is a factor in controlling the shape formation of a harvester's casing and the position of an air grid. Ensuring a decrease in the airflow velocity at the outlet from the channel is an a priori condition for the operation of stripping devices. In this case, the curvilinear shape of the casing is limited to a boundary zone, characterized by a zero value for airflow velocity (Fig. 4, 5).

Modeling the process of separation of a stripped pile in the region of a harvester with the derived shape of its casing implies taking into consideration the initial orientation, the motion velocity of a pile's components, and their physical-mechanical properties (Table 3). It should be noted that the criterial estimate of the quality of a separation process depends on the level of variation for factors of numerical modeling (Table 4). These factors are: the mass yield of related components from a harvester Δ_h (husks, segments of the stem, etc.), as well as seeds and boxes of flax Δ_s.

The visualization of the distribution process of a pile's components in the region of a harvester (Fig. 7) and the dependence of their mass share of yield (Fig. 8) on the experimental factors might act as a basis for solving a compromise problem. It implies minimizing the yield of related components of a pile and maximizing the yield of seeds.

Based on the research results, the following rational structural-technological parameters for a harvester with the obtained curvilinear shape of its casing have been defined: the rotation frequency of a beat-reflector n_1=782 rpm, the rotation frequency of a stripping rotor n_2=671 rpm, the position of a transparent zone of boundaries L=0.82 m and its width B=0.45 m.

Comparing the results from a body of research aimed at substantiating the rational parameters for harvester of the stripping type [8–10, 13] revelas the appropriateness of taking into consideration the influence of an air flow and the properties of a stripped pile's components.

It is obvious that the feasibility of advancing the chosen field of research is predetermined by the need to develop and improve a set of methods aimed at solving tasks that arise when creating and implementing the combine-harvester-based technique for harvesting agricultural crops by stripping plants at the root.

6. Conclusions

1. The result of our numerical modeling of the aerodynamic processes in a harvester of the stripping type is the established distribution of air flow velocities in its region and the derived dependence of maximum air velocity $V_{\max}$ on the rotation frequency of a beat-reflector n_1 and a stripping rotor n_2 and the position of a transparent zone of boundary *L*.

The result of our numerical modeling of the process of a pile separation in a harvester of the stripping type with a curvilinear shape of its casing taking into consideration the physical-mechanical properties of its components is the established dependences of the mass share of the yield of husks and segments of the stem from its region (a quality score for cleaning a pile from impurities) Δ_h and the share of yield of seeds and boxes with seeds (an indicator for seed losses) Δ_s on the rotation frequency of a beat-reflector n_1 and a stripping rotor n_2, the position of a transparent zone of boundary *L* and its width *B*.

That predetermines defining the rational shape of a harvester's casing and the position of regions of a transparent boundary in order to ensure the high-quality progress of the technological process.

2. By solving a compromise problem, namely, minimizing the share of yield of related components Δ_h and maximizing the share of yield of seeds and boxes with seeds Δ_s, we have defined the structural-technological parameters for a stripping harvester. These parameters are: the rotation frequency of a beat-reflector $n_1=782$ rpm, the rotation frequency of a stripping rotor $n_2=671$ rpm, the position of a transparent zone of boundaries $L=0.82$ m and its width $B=0.45$ m.

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