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STUDY OF THE PROCESS OF GRAIN PRE-THRESHING BY WORKING BODIES OF A COMBINE HARVESTER HEADER

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Досліджено технологічний процес обмолоту зернових культур пристроєм попереднього обмолоту зерна жниварки зернозбирального комбайна. Розроблено експериментально-розрахунковий метод оцінювання рівня відділення зерна пристроєм. Отримано теоретичну залежність коефіцієнта відділення зерна, яка встановлює системний взаємозв'язок між параметрами та режимами функціонування пристрою жниварки та зернозбирального комбайна. Експериментально встановлено залежності коефіцієнта відділення зерна від швидкості руху комбайна

Ключові слова: зернозбиральний комбайн, жниварка, пристрій попереднього обмолоту зерна, коефіцієнт відділення зерна, маса відділеного зерна

Исследован технологический процесс обмолота зерновых культур устройством предварительного обмолота зерна жатки зерноуборочного комбайна. Разработан экспериментально-расчетный метод оценки уровня отделения зерна устройством. Получена теоретическая зависимость коэффициента отделения зерна, которая устанавливает системную взаимосвязь между параметрами и режимами работы устройства жатки и зерноуборочного комбайна. Экспериментально установлены зависимости коэффициента отделения зерна в зависимости от скорости движения комбайна

Ключевые слова: зерноуборочный комбайн, жатка, устройство предварительного обмолота зерна, коэффициент отделения зерна, масса отделенного зерна

1. Introduction

We can assume an increase of productivity and quality of agricultural aggregates, including combine harvesters at the present stage of development of agricultural mechanization. A combine harvester is a main harvesting machine. The effectiveness of all works related to harvesting of grain crops depends on it [1].

One of the financially attractive types of activity of a modern farmer is the cultivation and further application of seeds as a seed material. We spend more than 3.5 million tons of seeds for sowing cereal and industrial crops annually in Ukraine alone. It makes up 8–10 percent of gross harvest [2]. However, perfection of both technological methods of cultivation and successful methods of harvesting and further processing of a crop, which damage grain minimally, largely determines success in this direction. Significant damage and injuries of seeds during harvesting and its initial processing cause poor quality of seed material. Therefore, we obtain discrepancy with basic indicators that are applied to seed material. Agrarians increase a rate of sowing by 20–25 % compared to sowing of conditioned seeds in response to such circumstances [3, 4]. Research was conducted that established the possibility of separation of up to 35 % of grain by operative parts of a header [5, 6].

Underlying a research hypothesis is the possibility of intensification of the process of separation of grain from grain and straw mass (GSM). Such separation occurs due to interaction of GSM with a header device of preliminary threshing at the phase of transportation of GSM to the threshing-separation system (TSS) of a combine harvester. We should note that pre-threshed grain subsides (concentrates) in a lower part of a flow of technological mass and a thrashing drum does not damage it. Separated grain passes through a grid concave faster. It is known that it helps to reduce grain losses in straw behind thresher. Therefore, we can conclude that it is expedient to apply the preliminary threshing of grain by operative parts of a header before a cut technological material gets into an inclined conveyor.

A need to increase productivity of a combine harvester and to reduce fluctuations in the supply of bread mass and injuries of grains explains the relevance of the study. We can achieve desired results if we improve a system of transportation of threshed product from a screw of a header to a conveyor of an inclined chamber. There is a threshing and transporting device (a device for preliminary threshing of grain) in a space between a screw of a header and a conveyor of a combine harvester.

2. Literature review and problem statement

Efficiency of technological processes of threshing and grain separation, as well as a level of grain damage, determine productivity of a combine harvester [7]. It is extremely important to ensure the most efficient separation of grain in TSS of a combine, since an increase in a number of grains that passed through a concave of a thrashing drum reduces a load on a straw rake or other coarse pile separator. Such conditions reduce grain losses and increase productivity of a grain combine harvester.

The research on the influence of parameters of a grain harvester combine on the distribution of grain in TSS established the degree of threshing of grain by threshing devices of multi-drum TSS [8]. It was noted that an increase in the speed of a combine (loading of TSS) leads to redistribution of grain separation volumes between drums [8].

Technical parameters of a threshing machine, as well as conditions and modes of grain threshing cause losses of grain in TSS of a grain combine harvester. Research [9] proposed an analytical model of a grain loss index for a threshing machine of a combine harvester, which depends on a moisture content of straw, a feeding of technological mass for threshing, straw content of technological material and an effective length of an integrated grain separation system. It was noted that an increase in the humidity of straw, or straw content, causes a corresponding increase in grain losses in straw [9].

The probabilistic function describes grain distribution in TSS of a combine in the differential parametric model [10]. There are distribution functions constructed for different values of mass entering a combine thresher.

Paper [11] presents a stochastic mathematical model of processes of threshing and separation of grain in threshing machines of tangential and axial types. The obtained dependences describe a proportion of non-threshed, free and separated grain depending on the length of TSS.

A model [12] describes physical separation of grain from plant material in TSS of a combine depending on a flow rate of a material, its bulk density, thickness of a separating layer and a diffusion coefficient. This model determines a value of a separation coefficient of grain depending on a current position and length of TSS of a combine.

Studies [13] proposed to forecast separation of grain in TSS of a combine by an artificial neural network, which makes it possible to determine an effect of a gap between a drum and a concave, a speed of a drum, a length of stems, and a mass feed on a grain separation value.

The overwhelming majority of specialists characterize a process of threshing of grain mass as a process, which occurs due to TSS action of a combine harvester only. We cannot take into account a dynamic effect of other operative parts of a header and combine harvester on mass transported to TSS under such conditions.

However, on the way to TSS, interaction of operation parts with grain and straw mass makes it possible to weaken connections of grains with a cone, and sometimes to separate it entirely [14]. A process of grain threshing starts from a moment when reel fingers of a header begin to interact with a stem. A degree of separation of grain from mass transported by a harvester depends on many factors: phases of development of a crop, humidity, ripeness, variety, dynamic components of a plant, etc.

There is a space plate between a header and a body of an inclined chamber of a combine harvester in «Slavutich» KSZ-9 grain harvesters. A space plate provides the alignment of a flow of plant mass and simplifies a process of a header assembly. It consists of a body and a beater equipped with an eccentric finger mechanism. A beater of a space plate transports bread mass from a header to an inclined chamber. The mechanism does not implement a function of preliminary threshing in KZS-9 «Slavutich» grain combine harvester.

A space plate should reduce unevenness of feeding and traumatizing of bread mass due to improvement of conditions of transportation of a product, which is threshed. Sometimes a space plate, or a node, which can be placed instead of it, implements a task of preliminary grain threshing.

Under conditions of research into wheat harvesting, grain combine harvesters with a harvesting part equipped with a preliminary grain threshing machine provided an increase in the throughput by 24 % in average and had almost identical grain refining rates with serial combines [14].

Disadvantages of known preliminary grain threshing machines [15] include low technological reliability. In addition, in most of them, operative parts of a harvesting section transport mowed mass into a threshing machine in the state, in which it was formed on the cutting unit – in portions, unevenly, interspersed [16]. This leads to a decrease in productivity of combine TSS, as well as a deterioration in a quality of a threshing index [17]. This is especially significant for the harvesting of tangled, long-stemmed crops [18].

A high level of damage to seeds characterizes technological processes of harvesting and preliminary processing of cereals under conditions of Ukrainian agricultural production. Seed promotion to European and world markets is limited due to this fact. Publications do not cover the question of evaluation of effectiveness of mechanisms that implement grain separation from GSM at stages of movement through an inclined chamber of a header sufficiently. That is why the study of the combined threshing and transporting technological process, which is carried out by a device of preliminary grain threshing, and the evaluation of efficiency of its operation under conditions of minimum level of trauma of grain by operative parts of a header of a combine harvester are quite promising tasks.

3. The aim and objectives of the study

The aim of present study is to reduce trauma of seeds and to increase productivity of a grain harvesting combine by improvement of technological processes and technical means of transportation and threshing of grain by a header.

The following tasks were solved to achieve the objective:

– conduction of experimental investigation on developed devices of the preliminary separation of grain and determination of a rational structural and technological scheme of a device;

– determination of the effect of a quantity and height of stops on a drum of a device on a value of a coefficient of separation of grain, depending on the speed of a combine;

– development of a method for quantitative evaluation of the amount of grain separated by the developed device;

– establishment of a theoretical dependence of a grain separation coefficient on parameters and operating modes of a header of a combine harvester.

4. Materials and methods of the study into degree of separation of grain by a header device

We used KZS 9-1 «Slavutich» grain harvester to carry out experimental researches. Its header had a device for preliminary threshing of grain. Kherson machine-building plant manufactures the family of KSZ 9-1 «Slavutich» Ukrainian grain harvesters.

The development of a device for preliminary grain threshing included the development of a design and construction of a drum with removable operative parts (bars with a different form of teeth) (Fig. 1). The design of a drum provided the possibility of installation of two or four bars. The height of bars was 20 or 30 mm, the profile of a bar was smooth or tooth-shaped.

We installed the drum in the space plate of the header instead of a beater equipped with a finger mechanism. The rotational speed of the drum changed due to a specially made set of chain-drive sprockets with the number of teeth 15, 17 and 19 pcs.

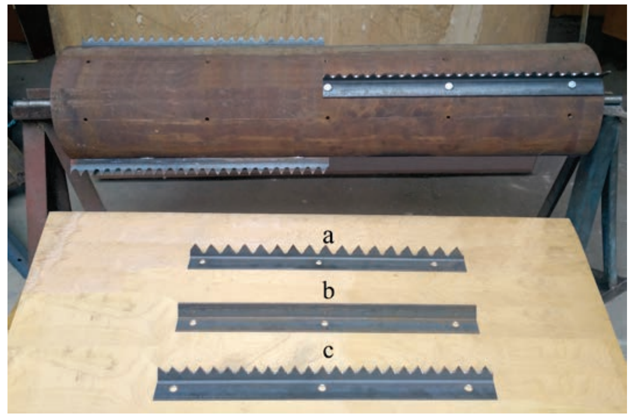


Fig. 1. Intermediate thrashing drum and options of additional drum bars: *a* — smooth; *b* — with tooth-shaped profiles and of 30 mm height; *c* — with tooth-shaped and of 20 mm height of the device of preliminary grain threshing

The experimental research program provided:

– tests of an intermediate cylindrical space plate with fingers, which hide (a serial header);

– tests of an experimental header, which contains a cylindrical tooth and spatulate shaped drum with a diameter of 330 mm without additional bars (smooth drum);

– test of a header with an intermediate thrashing drum with a whip under a drum;

– test of a header with an intermediate thrashing drum, which contains two additional bars. Profile of a bar – smooth, tooth-shaped with a height of a bar 20 mm, tooth-shaped with a height of a bar 30 mm;

– test of a header with an intermediate thrashing drum, which contains four additional bars. Profile of a bar – smooth, tooth-shaped with a height of a bar 20 mm, tooth-shaped with a height of a bar 30 mm.

A rectangular steel triangle (45×45 mm in size) was used as bars. We attached one side of it to the side of the drum. On the other side of the triangle, we cut the tooth-shaped profile in the form of equilateral triangles with a height of 20 mm and 30 mm (Fig. 1).

4. 1. Materials and equipment examined in the study

The study program provided alternate experiments with headers containing the above-mentioned thrashing drums (according to the list in Chapter 4).

4. 2. Method for determining a degree of grain separation by a header device

The method of the study included selection of a site with homogeneous and aligned stems. We conducted experiments at the research sites of the National Scientific Center «Institute of Mechanization and Electrification of Agriculture» of the National Academy of Agrarian Sciences of Ukraine. They are planted with winter wheat of Mironivska 61 grade. The research was conducted according to standard methods [17, 18]. The crop capacity of the field was 55 c/ha.

Changes in the transmission relation of a chain drive controlled the rotational speed of the drum shaft.

There were three speeds of the combine harvester: 2, 4 and 6 km/h in three replicates.

During experiments, we fixed: a length of the experimental site, time the combine passed the experimental area, speed of the combine, the area of the site under investigation. Based on the results of each test taken from a rock chamber located in front of the main thrashing drum of the combine, the mass that was accumulated there was selected. The mass was a mixture of grains separated from cones, non-threshed grain in a cone, heap and straw. We poured mass, which was accumulated in a rock bunker, to specially prepared pre-signed packages. We carried out the processing of research results under laboratory conditions.

Under laboratory conditions, as a result of disassembly, we determined samples taken in the field: the mass of separated grain – m_g, the mass of nonseparated grain – m_{ng}. The total mass of grain in GSM was $M_g = m_g + m_{ng}$.

We determined the mass of straw by the ratio of grain to straw by weight 1: 1, 2, i. e.

$$M_s = 1.2 M_g = 1.2 \cdot (m_g + m_{ng}).$$

We used methods of regression analysis for processing the results of experimental studies. We performed the approximation of experimental dependencies by a mathematical model with the use of the least squares method by STATISTIKA-6.5 statistical software package. We checked the adequacy of mathematical models using elements of variance analysis employing the Fisher's criterion at a confidence probability level of 0.95.

5. Results of the study into degree of grain separation by a header device

The basis of the device for preliminary threshing of bread mass in the combine harvester was an intermediate thrashing drum and a deck installed below it (Fig. 2). The drum was made in the form of a cylinder with a diameter of 330 mm with tangentially fixed bars on its surface (Fig. 1). A deaf (without holes) cylindrical deck with an angle of 56° was eccentrically installed under a drum with the ability to adjust gaps at the inlet and outlet. We also investigated the intensification of the threshing process by installation of decks of corrugated whips on the surface.

According to the results of comparative experimental studies, we found that the tooth and spatulate shaped thrashing drum grinds significantly more (by 30–35 %) grain compared to the standard beater of a space plate. The amount of grain deposited in the rock bunker (in front of the main thrashing drum) depends on a shape (design) of a thrashing drum for preliminary threshing and its rotational speed.

We evaluated the performance of the device for preliminary grain threshing by a special indicator. The indicator characterizes the consistency in the system of harvesting and threshing of crop of a number of technical and operational indicators and factors comprehensively.

We carried out the evaluation of the efficiency of separation of grains from cones by the device of preliminary grain threshing by calculation and experimental method based on analysis of the ratio of mass of the separated grain to the mass of grain, which was expected to arrive:

$$k_s = \frac{m_g}{m_{\exp.g}}, \qquad (1)$$

where m_g is the mass of grain separated by the device (established experimentally), kg; $m_{\exp.g}$ is the mass of grain expected to reach the inclined chamber of the device according to results of the experiment (determined by the calculation method), kg.

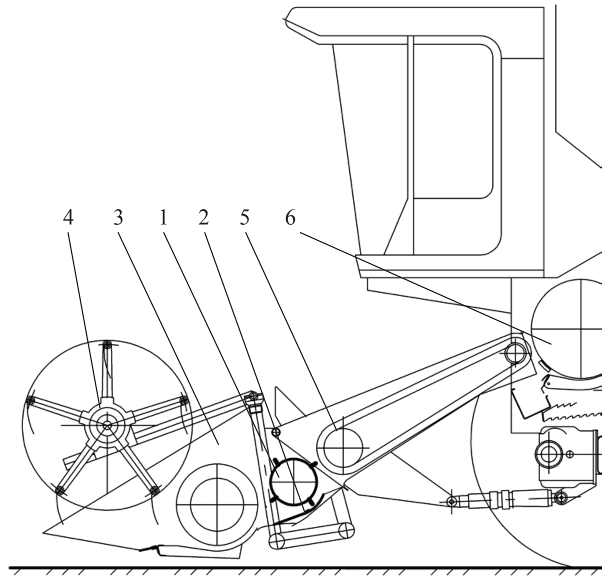


Fig. 2. Schematic of general view of a header of a combine harvester with a device for preliminary grain threshing: 1 — a tooth and spatulate shaped thrashing drum; 2 — a deck; 3 — a header; 4 — a reel; 5 — an inclined chamber conveyor; 6 — TSS of combine harvester

The coefficient of grain separation from a cone (k_s), together with the absolute value of mass of this grain (m_g) makes possible to evaluate constructive and technological and technical decision regarding the device of preliminary grain threshing.

GSM arrives to the device of preliminary grain threshing. The total quantity of GSM coincides with the mass arriving to the threshing machine. According to [1–6], we determined the amount of the mass (bandwidth, q, kg/s) by dependence:

$$q = \frac{B \cdot k_f \cdot v_M \cdot Q}{360}, \qquad (2)$$

where Q is the crop capacity of grain and straw, c/ha: $Q = Q_g + Q_g \cdot \beta$; Q_g is the crop capacity of grain, c/ha; β is the share of straw by weight relative to crop capacity of grain; B is the width of a grip of a header, m; v_M is the speed of a combine harvester, km/h; k_f is a coefficient of efficiency of a use of a width of a grip of a header (according to experimental data, the value of this coefficient varies within the range of 0.94–0.99).

A width of a grip of a header was 6 m.

Following simple transformations, we obtained:

$$k_s = \frac{m_g}{m_{\exp.g}} = \frac{5 \cdot m_g}{18 \cdot q \cdot l_i} \cdot v_M \cdot (1 + \beta), \qquad (3)$$

where l_i is the length of the experimental site, m.

Fig. 3–5 show dependence of the grain separation coefficient (k_s) on various factors. The length of the experimental site (length of a combine harvester) has a significant effect on the grain separation coefficient (Fig. 3–5). Increasing the length of the site leads to a decrease in the grain separation coefficient. This is due to the fact that a volume of the rock chamber, from which samples of threshed grain were carried out, is limited, which, on long runs, results in distortion of measurement results.

An increase in the mass fraction of straw on grain crop capacity also results in an increase in the grain separation coefficient (Fig. 3).

Analyzing dependence (3) and the constructed graphic dependences (Fig. 3–5), we can note that conditions for maximum separation of grain appear for small values of the throughput and the length of the run (q=2 kg/s, l_i=6 m, Fig. 3) in the inclined chamber of the header. The grain separation coefficient was 0.93 under such conditions. That is, in fact, 93 % of grains entering the inclined chamber of the header were separated from cones. This grain is deposited in the lower part of the inclined chamber and forms its flow.

With an increase in the speed of a combine, the value of the grain separation coefficient increases (Fig. 4). Thus, the speed of 2 km/h corresponds to k_s=0.1; under conditions υ_M=6 km/h – k_s=0.3; under conditions υ_M=10 km/h – k_s=0.5, respectively.

Fig. 6, 7 show results of experimental studies into determination of a degree of grain separation by a serial header compared with the header, which contains the device for preliminary grain threshing.

We should note that increasing the speed of the combine results in an increase in the grain separation coefficient for all investigated samples (Fig. 6, 7). However, it was not possible to carry out experiments on a smooth drum header on the maximum planned research speeds for the header, the drum of which contained a whip.

There were cases of reduction of the speed of a combine in the course of the mentioned experimental studies. This happened due to the deterioration of the combine's throughput, which occurred due to the accumulation of grain-straw mass at the input of the device for the preliminary threshing, which the device did not accept. That is, the amount of mass that came to the inclined chamber of the header did not correspond to the functional capacity of the device. This led to a forced reduction in the speed of the combine (reduced throughput).

According to the results of the conducted research, the value of the grain separation coefficient for a serial combine that contained beater with hiding fingers was at the level of 0.04–0.06.

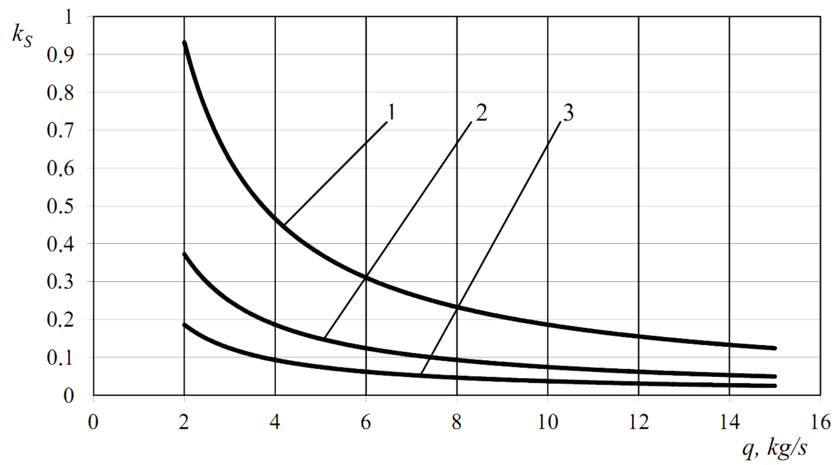


Fig. 3. Calculation and experimental dependences of the separation coefficient of grain (k_s) on the throughput (q) under conditions m_c=3.5 kg; β=1.3; ν_M=5 km/h, for various l_i: 1 – l_i=6 m; 2 – l_i=15 m; 3 – l_i=30 m

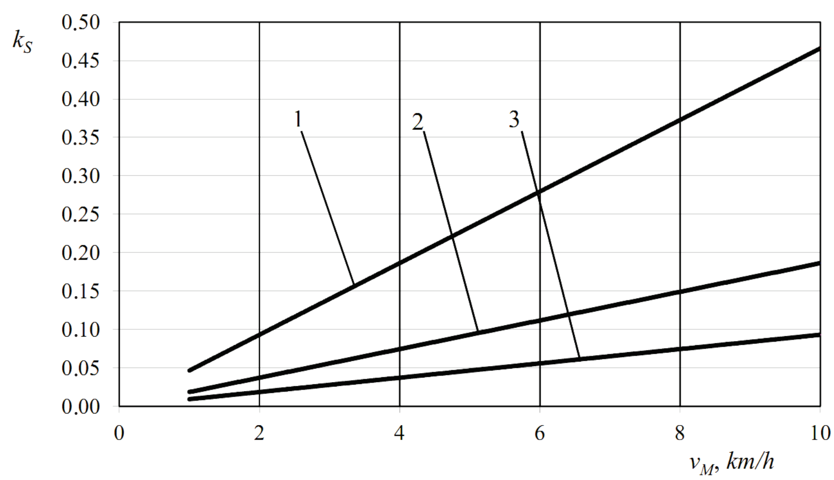


Fig. 4. Calculation and experimental dependences of the grain separation coefficient (k_s) on the combine harvester speed (ν_M) under conditions m_c=3.5 kg; q=8 kg/s; β=1.3, for different l_i: 1 – l_i=6 m; 2 – l_i=15 m; 3 – l_i=30 m

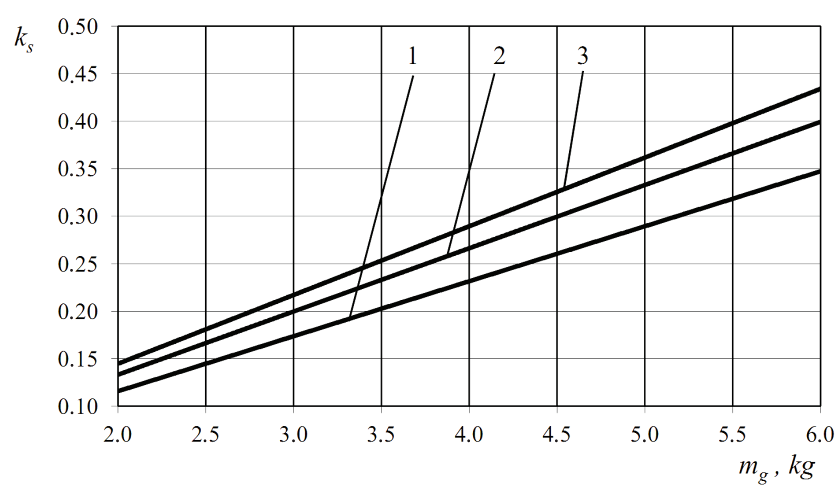
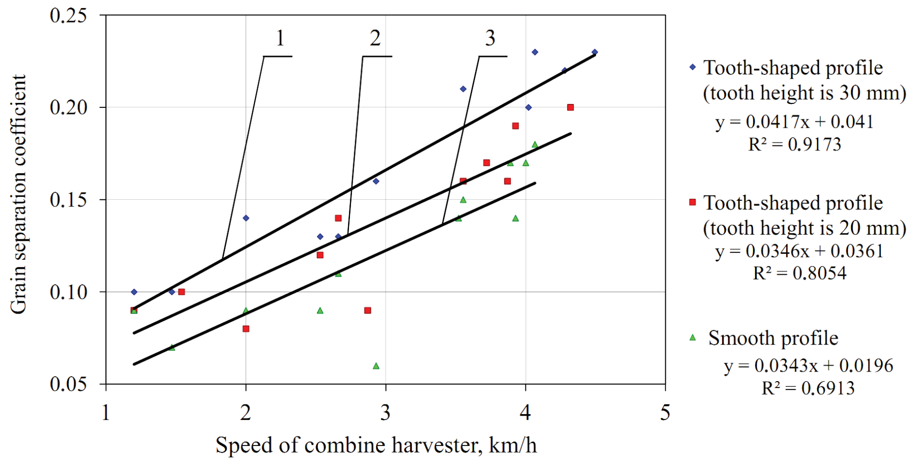
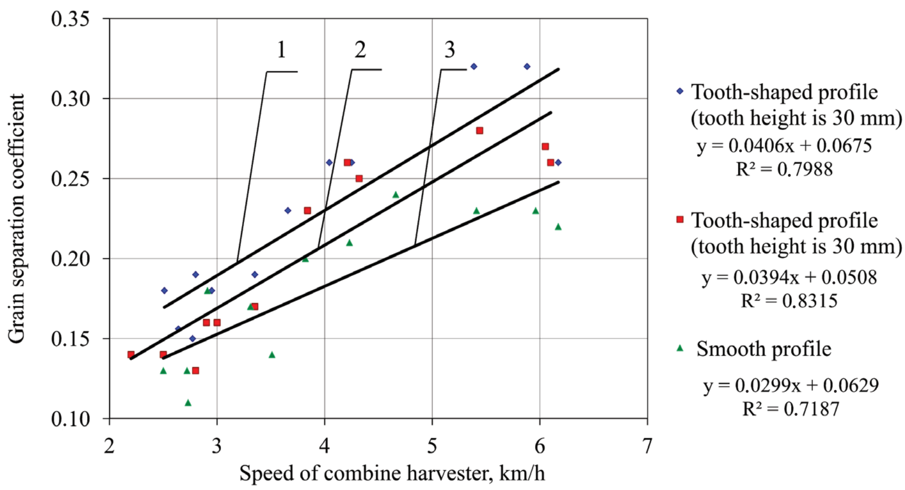


Fig. 5. Calculation and experimental dependences of the separation coefficient of grain (k_s) on the mass of the grain separated by the device by l_i=6 m; ν_M=5 km/h; q=8 kg/s for various β: 1 – β=1.0; 2 – β=1.3; 3 – β=1.5



a



b

Fig. 6. Experimental dependences of grain separation coefficient (k_s) on combine speed: *a* – for a header with an intermediate thrashing drum, which contains two additional bars; *b* – for a header with an intermediate thrashing drum, which contains four additional bars: 1 – a tooth-shaped profile with a height of a bar 30 mm; 2 – tooth-shaped profile with a height of a bar 20 mm; 3 – profile with a smooth bar

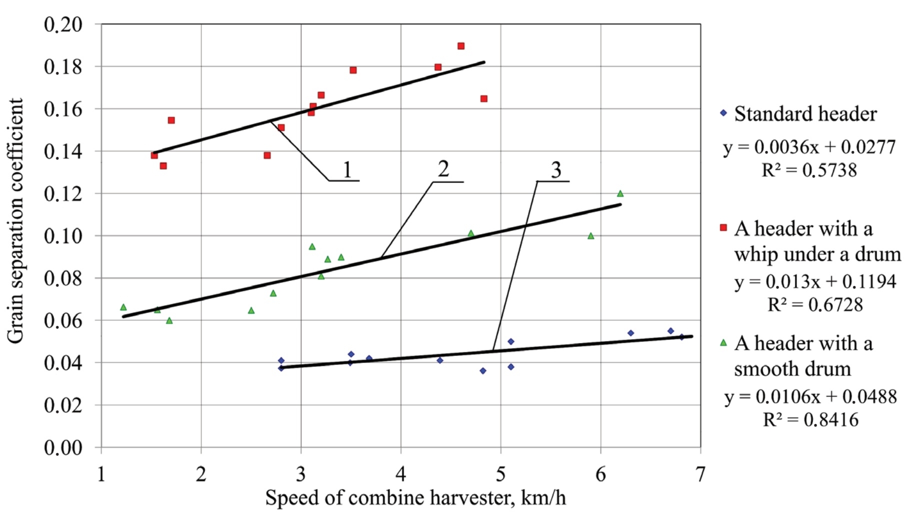


Fig. 7. Experimental dependences of the grain separation coefficient (k_s) on combine speed: 1 – a header with a whip under a drum; 2 – a header with a smooth drum; 3 – standard header

Thus, at the speed of the combine 5.1 km/h, weight of the separated grain on the area of 33.5 m^2 was 0.865 kg, and the value of the separation coefficient was 0.05. At the speed of 6.7 km/h and the experimental site area of 27.6 m^2, the weight of the separated grain was 0.785 kg, and the value of the separation coefficient was 0.06.

The value of the grain separation coefficient for an experimental header, which contained a cylindrical toothed spatulate shaped drum of 330 mm in diameter without any additional bars (smooth drum), varied within 0.06–0.12. At the speed of the combine 6.2 km/h and the area of 31.2 m^2, weight of the separated grain was 1.93 kg, the value of the separation coefficient was 0.12. The lowest value of the grain separation coefficient (0.06) for this device was at a combine speed of 2.5 and a site area of 38.8 m^2 – mass of separated grain was 1.30 kg.

At tests of a header with an intermediate thrashing drum with a whip under a drum, the value of the grain separation coefficient varied in the range of 0.14–0.18. We detected lower value of the coefficient of the separation (0.14) at the speed of the combine of 1.53 km/h and the area of the site of 30.0 m^2, the mass of the separated grain was 2.14 kg. The highest value (0.18) for this device for preliminary grain separation was at the combine's speed of 4.37 km/h and the area of the site of 29.4 m^2, the mass of the separated grain was 2.73 kg.

We conducted the research of a header with an intermediate thrashing drum, which contained two additional bars in three variants. At the first option, we examined the device with smooth bars attached to its drum; at the second one – the device with a drum, which contained tooth-shaped bars with a height of a bar 20 mm, at the third one – the device with a drum, which contained bars of the tooth-shaped profile with a height of a bar 30 mm, respectively. We established that for the device with smooth bars attached to the drum, the speed of the combine was 2.53 km/h, the weight of the separated grain on the area of 35.3 m^2 was 1.64 kg, and the value of the separation coefficient was 0.09. The highest value (0.17) for this device for the preliminary grain separation was at the combine speed of 3.89 km/h and the area of 33.5 m^2, the mass of the separated grain was 2.94 kg. For the device with a drum, which contained two bars of the tooth profile with a height of 20 mm, the speed of the combine was 2.0 km/h, the weight of the separated grain on the area of 35.3 m^2 was 1.46 kg, and the value of the separation coefficient was 0.08. The highest value (0.19) for this device of the preliminary grain separation was at the speed of the combine of 3.93 km/h and the area of 31.2 m^2, the weight of the separated grain was 2.57 kg. For the device with a drum, which contained two bars of the tooth profile with a height of 30 mm, the speed of the combine was 4.49 km/h and the mass of the separated grain on the area of 33.5 m^2 was 3.98 kg, and the value of the separation coefficient was 0.23. The value of the grain separation coefficient (0.09) for this device was at the speed of the combine of 1.2 km/h and the area of the site was 31.2 m^2, the mass of the separated grain was 1.45 kg.

We conducted a technological process of transportation and threshing of GSM carried out by the intermediate thrashing drum with four additional bars in three variants, similar to those of drum research with two bars. According to the results of tests of a header with an intermediate thrashing drum containing four smooth bars, the value of the separation coefficient of grain varied in the range of 0.11–0.22. The lowest coefficient of the separation (0.11) was at the speed of the combine of 2.73 km/h and the area of the site 27.6 m^2, the weight of the separated grain was 1.57 kg. The highest value (0.22) for this device of the preliminary grain separation was at the speed of the combine of 6.17 km/h and the area of 37.6 m^2, the weight of the separated grain was 4.27 kg. For the device with a drum, which contained four bars of the tooth profile of a height of 20 mm, the speed of the combine was 2.8 km/h, the weight of the separated grain on the area of 28.2 m^2 was 1.89 kg, and the value of the separation coefficient was 0.13. The highest value (0.28) for this device of the preliminary grain separation was at combine speed of 5.44 km/h and the area of the site of 39.4 m^2, the mass of the separated grain was 5.69 kg. For the device with a drum, which contained four bars of the tooth profile with a height of 30 mm, the speed of the combine was 5.39 km/h, the weight of the separated grain on the area of 36.8 m^2 was 6.07 kg, and the value of the separation coefficient was 0.32.

According to the results of the conducted research into combined process of transportation and threshing of GSM, we established that the device with a drum, which contained four bars of the tooth profile with a height of 30 mm, performs transportation of the mass and provides stable threshing of up to 32 % of the grain.

During the mathematical processing of the results of experimental studies, we determined statistical characteristics: mathematical expectation, dispersion, mean square deviation, and coefficient of variation according to works [19, 20].

We fitted empirical distributions with theoretical ones according to statistically developed criteria specially developed in theory [19, 20].

6. Discussion of results of the study into degree of grain separation by a header device

The conducted research established the possibility of threshing of 30–35 % of grain before the arrival of technological mass to the main TSS of a combine.

We should note that that a drum of a preliminary threshing machine without hiding fingers performs also a function of mass doser. Under conditions of supplying technological mass more than TSS combine can process, a drum of the device does not pass it into an inclined camera. This makes possible to reduce damage and losses of grain by a combine. The developed design simplifies construction of a header by replacement of the rather complex beater with hiding fingers with a drum of a tooth spatulate shaped type.

According to the results of the research, we improved the combined technological process of transportation and threshing of GSM. We achieved the effect of threshing due to the developed device of preliminary grain threshing of a header of a grain harvester KZS 9-1 «Slavutich» (Fig. 1, 2). Application of the device makes it possible to separate 30–35 % of grain at the early phases of its transportation to TSS of a combine.

The technological process of transportation of GSM through the inclined chamber of a header is a complex process of motion. The increase in a grain share in a total mass flow goes constantly in this process due to the separation of grains from cones.

The following features characterize movement of GSM:

– separation of individual grains, halves and others from inflorescences of cut stems, settling in the lower part of the flow of technological mass, which is heavier than the straw of a grains fraction;

– formation of a separate grain flow out of separated grains;

– injuries of grain in early stages of its transportation.

We achieved the highest level of separation of grain from GSM with a harvester with an intermediate thrashing drum with four additional bars, the tooth-shaped profile of which had a bar height of 30 mm. The grain separation coefficient for such a device was at the speed of combine $v_M=5$ km/h, $k_s=0.15$, at the speed $v_M=6$ km/h $k_s=0.30$ (maximum k_s value $=0.32$ reached at the combine harvesting capacity at the level of 12 kg/s).

We considered the movement of GSM with the following assumptions: it was a homogeneous mass consisting of stems of straw and cones with grain at the beginning of mass entering the device for preliminary grain threshing. The mass deforms and compresses due to the dynamic effect of stops of the drum. There is a partial destruction of links between grains and cones, and often separation of grains from cones. The mass density makes it possible to move free grain into the lower part of the space formed between the stop of the drum and the drum. Thus, in this zone, we get formation of the flow of free grains over some time. We should note that the movement of separated grain no longer occurs in conjunction with the main part of GSM. Transportation of this mass is not uniform, it goes in portions. The layer of threshed grains is not deformed.

On a site that represents the beginning of mass transportation through a preliminary threshing device, there is an accumulation in volume equivalent to the volume between two adjacent stops and a deck. The resulting stopper was then compressed and pushed further. The edges performed the function of squeezing the mass, strain and transporting through the inclined chamber. The transportation function was consistent with kinematic parameters of mechanisms that supplied and accepted GSM.

The device's stops interact with GSM stems. Movement of GSM occurs in the flow of interwoven wheat stems (or other grain crops). The stop compressed (deformed) stems and moved them as a continuous infinite ribbon through the inclined chamber.

The profile of the hole, which forms the stop in GSM under conditions of its movement, is determined by a curve line, tangent to the sides of the stop, under arbitrary positions.

It should be noted that as a result of the interaction of the front surface of the stop there is a deformation of GSM and, as a consequence, the destruction of the links between the grains and cones. The grains are separated from the colostrum and accumulate on each layer of GSM gradually deposited as a result of forces of gravity on the surface of the inclined chamber, forming their own grain flow.

An increase in the thickness of the grain mass flow in the total volume of moving GSM leads to an increase in the resistance forces of the movement. This happens due to the gradual decrease in the height of the gap between the stop of the drum and the lateral surface of the inclined chamber. Reducing the gap leads to an increase in the deformation of GSM, and as noted above, to increase in the separation of grains from cones.

Reduce of the gap and increase in the resistance forces of GSM movement can cause clogging of the inclined chamber. Modern combine harvesters have special devices to prevent such phenomena. Devices provide an increase in the clearance between a drum and a deck under certain conditions. Such conditions reduce the forces of resistance of movement of GSM and the whole mass goes through the technological channels of the combine for subsequent operations.

In the case of clogging of the inclined chamber, the degree of deformation of GSM increases significantly, which negatively affects grain that was already separated from cones. The energy consumption per unit volume of deformation increases.

We determined regression equations that adequately describe the dependence of the grain separation coefficient k_s on the speed of a combine (Fig. 6, 7). The fluctuation of values of the correlation coefficient in the range 0.672–0.971 indicates that for a standard header (correlation coefficient 0.685, for a header with a whip – 0.672) an average index (the correlation coefficient value is $0.50 < r < 0.69$) characterizes the correlation coupling force. For all other cases, the value of the correlation force corresponds to the presence of a strong (dense) bond (correlation coefficient $r > 0.70$). The sign of the correlation coefficient is positive, which makes it possible to characterize a link between correlating features by the following: the larger value of one sign (variable) corresponds to the larger value of another sign (another variable) [19, 20]. We should note the existence of a directly proportional relationship between two indicators under study. In other words, if one indicator (variable) increases, then another indicator (variable) increases accordingly.

We can use the results of the conducted research for development of new and improvement of existing designs of devices of preliminary grain threshing of a header of a combine harvester.

7. Conclusions

1. We improved the combined technological process of transportation and threshing of GSM and developed the device of preliminary grain threshing for a grain header of KZS 9-1 «Stavutich» harvester, which made it possible to separate 30–35 % of grain in early phases of its transportation to TSS of a combine.

2. We determined the dependence of the grain separation coefficient on the speed of a combine experimentally. Dependences take into account cancellations of mechanized technological operations due to a change in kinematic operating modes of a combine, a number of stops and their height on a drum of the device of preliminary grain threshing. We established that the coefficient of separation of grain from cones in a header with an intermediate thrashing drum, which contains four additional tooth-shaped bars of 30 mm in height, has the highest (0.32) value.

3. We developed a calculation and experimental method for determining the amount (degree) of grain separation by a device of a header of a combine harvester. The method is based on the results of simulation of the combined process of transportation and threshing of grain caused by the interaction of a drum with grain and straw mass.

4. We analyzed and proved the complex influence of structural parameters of the device and modes of implementation of the combined process of transportation and threshing of GSM at the level of separation of grain. And this make possible to establish the theoretical dependence of the grain separation coefficient. The noted theoretical dependence gives possibility to substantiate rational parameters and operating modes of the device of preliminary grain threshing of a combine harvester analytically. System connections of technological operations of transportation and threshing of GSM realize the synergistic effect of increase in grain separation level.

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