MOVEMENT AND TRANSFORMATION OF GRAIN IN TWO-STAGE CRUSHER

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Abstract. Theoretical investigations of the grain movement and transformation parameters have been conducted in the technological process of crushed forage production. The value and direction of the grain velocity were determined while feeding it into the working area of the first stage crushing; a correlation of the basic parameters of the feeding device of the crusher was established with the value of the design and technological parameters of the rollers for crushing, which ensures the greatest throughput capacity of the crusher. A design and technological scheme of a two-stage crusher has been developed for forage grain. These investigations allow elaboration of a highly efficient two-stage grain crusher in the designing stage with minimal energy intensity of the working process and greatest efficiency.

Key words: crushing, grain, feeding roller, efficiency.

Introduction

In the practice of contemporary animal husbandry, application is ever increasing of a perspective and economically profitable way of forage grain preparation for feeding using the technologies of its crushing and preserving. Owing to good digestibility and assimilability of crushed grain the yields of milk of dairy cattle and weight of young animals increase noticeably, the quality indicators of milk and meat improve. This technology has also other advantages: crushing takes place without dust formation, which reduces dramatically hazard of pulmonary diseases of animals and environmental pollution, there is no forage waste after feeding, no need to crumble grain after drying, that is, one of the forage preparation stages is excluded.

A series of design solutions of machines for grain crushing are known [1-6]. However, investigations remain urgent in their optimisation, raising their efficiency and cutting specific energy consumption. Specifically, in familiar investigations [7-9] the technological process of grain deformation was studied when it passes through the working area of crushing; however, these investigations concern mainly the transformation processes and do not give a general idea about not less important processes of the grain movement in the crusher, which ensure optimal transformation – grain disintegration (crushing). We have worked out a fractional technology of crushing moist forage grain and a machine for its implementation – a two-stage grain crusher with three rollers for crushing [3; 4]. The efficiency of the work of the crusher, evaluated by the quality of the obtained product, energy intensity of the process and its productivity, depends on various factors: the pressure applied to the rollers which presses and destroys the grain material, frictional force of grain against the surface of the rollers, gap between the rollers, their diameter, rotational velocity, and so on.

The object of the work was a mathematical description of the movement process of grain and determination of the impact of individual parameters upon the most important indicators of the crusher performance.

Materials and methods

A general view of the design and technological scheme of the two-stage grain crusher and the technological process performed by it is presented in Fig. 1, a [5; 6], but the movement path of grain inside this machine – in Fig. 1, b. The technological process of the performance of the machine is the following. The grain material 1 is loaded into the hopper 2 and, after the aperture 3 is opened using the flap 4, it falls under the impact of the gravity force onto the feeding roller 5 where it is gripped by the grooves of the roller and fed through the supply canal 6 into the inter-roller gap 10 between the rollers 7 and 8 which grip the grain material and execute the first stage of crushing. After that the grain material is removed from the inter-roller gap 10 and directed along the curved plate 11 into the inter-roller gap 13 of the upper 7 and the lower 9 rollers executing the second stage of crushing. After that the crushed grain 13 is transferred onto the guide plate 14 and, moving along it, is treated with a preserving agent 15 (if grain is wet) from the nozzle 16, and discharged.
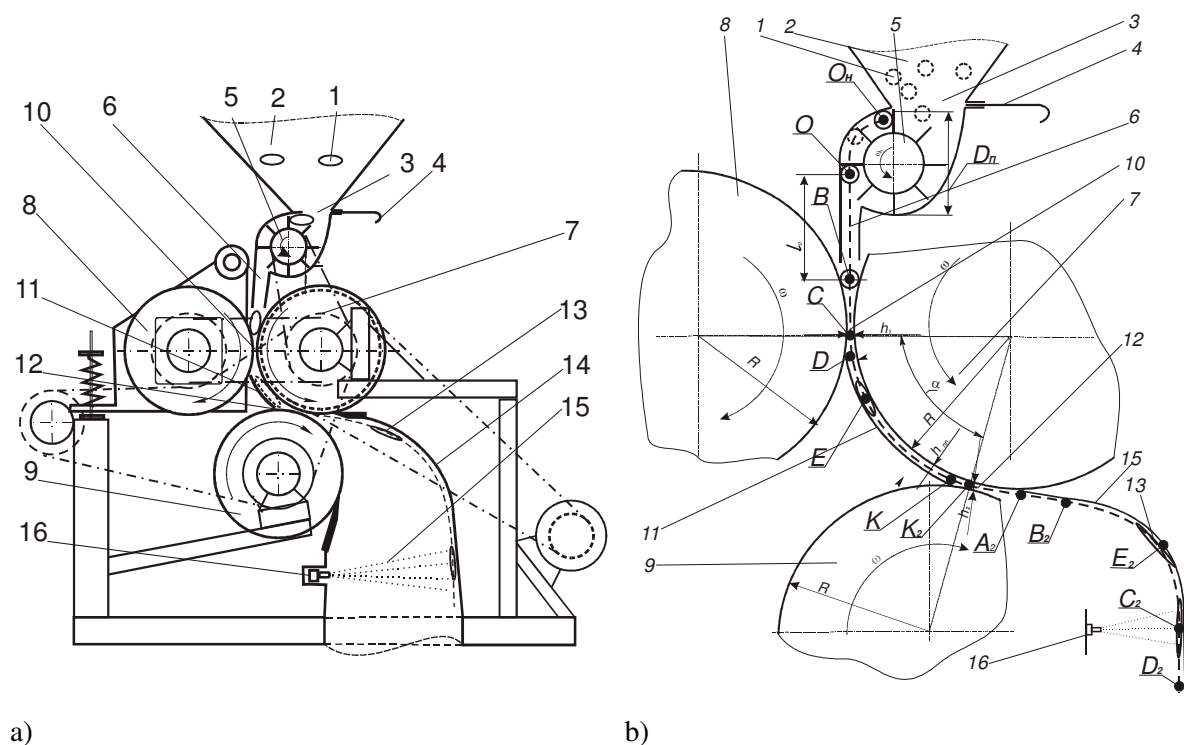
a)   b)

Fig. 1. **Technological scheme of a two-stage grain crusher with three rollers (a), and the movement path of the grain mass in the working area (b)**

All the technological operations performed by the developed machine can be conditionally divided into two groups: mechanical movements (*transportation*) and transformations [5]. The first group organises an uninterrupted technological process of producing crushed forage which includes the delivery of forage grain to the first stage of crushing in the required amount Q at the speed V_0 and in the necessary direction (a section of the grain material path O_HB – Fig. 1, b, the delivery of the previously destroyed (crushed) grain to the second stage of crushing in the amount $Q_1 = Q$ at the speed V_1, in the direction of the inter-roller gap of the second stage of crushing (section CK), the delivery of the crushed grain in the amount $Q_2 = Q$ at the speed V_2 into the area of its treatment with the preserving agent (section K_2C_2), (if grain is wet), and discharging the produced forage from the working area of the crusher (section C_2D_2). Transformation includes crushing of the first stage of forage grain (section BC in Fig. 1, b with a weighted average diameter d, its hardness T and moisture W, from value d to $d_1 = h_1$, where h_1 – the inter-roller gap of the first stage of crushing; crushing of forage grain of the second stage (section KK_2 in Fig. 1, b) from value $d_1 = h_1$ to $d_2 = h_2$, where h_2 – the inter-roller gap of the second stage of crushing which determines the required weighted average size of the flakes of the crushed forage; treatment of grain with a preserving solution (section in the area of C_2 in Fig. 1, b) in the necessary amount and its distribution within the grain mass. Optimal combination of mechanical movements and transformations determines the best technological performance of the crusher.

Let us allow certain idealisation of the flow of grain in our research and present it as the movement of individual grains. Individual grains 1 (Fig. 1, b), separating from the blade of the feeding roller 5 (point O), have certain initial velocity V_1, and they move down under the impact of the gravity force overcoming the resistance of air. After the grains have covered a certain distance l, they are transferred into the working area of the first-stage crushing (point B, Fig. 2), formed by the rollers 7 and 8, with the velocity V_0.

Rollers 7 and 8 rotate towards each other with an angular velocity ω, rad·s^{-1}, the linear velocity on their working (cylindrical) surfaces will be ωR, m·s^{-1}. The velocity of grain V_0 (at point B) should not exceed the linear velocity $V_e = \omega R$ of the working surfaces of the rollers for crushing 7 and 8 (accepting the limitation: $\omega R \geq V_0$) since in the opposite case there will clumping of grain before

crushing, dramatic deterioration of the conditions for gripping of grain by the rollers and, finally, significant decrease in the throughput capacity of the crusher occur.
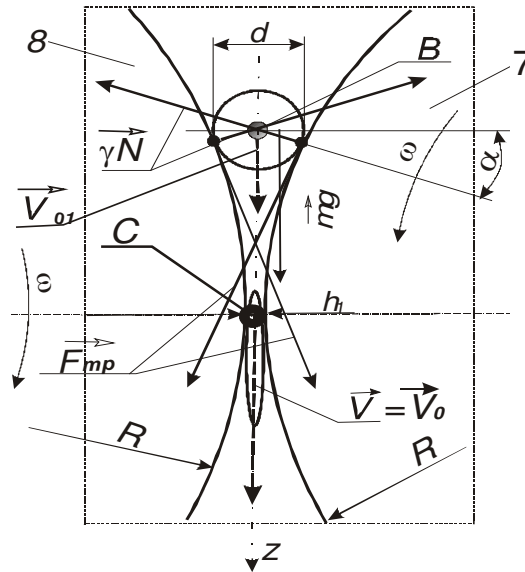

Fig. 2. **Movement of individual grains in the working area of the first-stage crushing**

Consequently, the grain gripped by the rollers at point *B* (the gripping conditions of grain by the rollers are known from previous investigations [1]), moves slipping a certain distance $l_{max} = BC$ (*BC* – Fig. 2 – the working area of the first stage of crushing) and moves with acceleration at the initial velocity V_0 (point *B*) to ωR (point *C*) (the movement in the inter-roller gap without slipping). After grain has covered the distance *BC,* it is crushed from the size $d = S_0$ to $h_1 = S$, where h_1 – the value of the inter-roller gap of the first crushing stage. The minimal time of passing the working area of the first-stage crushing $l = (BC)$ of the grain mass ensures maximal throughput capacity and, as a result, the efficiency of the crusher.

When individual grains with mass *m*, gripped by the rollers (Fig. 2), are moving with slipping, they are subject to the gravity force $\overrightarrow{mg}$ the friction force $\overrightarrow{F}_{mp}$ (we admit that it is constant), the force $\vec{P} = \vec{N}$, where $\vec{N}$ – a force pressing grain to the cylindrical surface of the crushing rollers.

The equation of the movement of individual grains will have the following general appearance:

$$\overrightarrow{mW} = \overrightarrow{mg} + \vec{F}_{mp} + \vec{P}, \tag{1}$$

where $\overrightarrow{mW}$ – the resultant of all forces acting upon an individual grain when its moves in the crushing area, which is directed vertically up (Fig. 2);

$\vec{W}$ – acceleration of a particular grain.

Let us project the expression (1) onto the axis *OZ* directed vertically down, and, considering the fact that the diameter of the roller for crushing $D_в = 2R$ is a little greater than the thickness of the grain mass *d* but the centres of the rollers for crushing are located in a horizontal plane (perpendicular to axis *OZ*) (Fig. 2), we obtain the following equation for the movement of the grains:

$$mW = mg + F_{mp}, \tag{2}$$

where $F_{mp} = Nf = Pf$;

f – friction coefficient of grain rubbing against the cylindrical surface of the roller for crushing;

P – average value of the specific force (a constant value for a selected working condition of crushing) [7; 8];

$W = \dfrac{dV}{dt}$ acceleration of grain as an instantaneous change in its velocity.

Results and Discussion

After corresponding substitutions into equation (2) we obtain the following equation for the movement of grain:

$$m\frac{dV}{dt} = mg + F_{mp}, \tag{3}$$

$$\frac{dV}{dt} = g + \frac{F_{mp}}{m}. \tag{4}$$

After integration of dependence (4) we obtain an expression for determination of instantaneous velocity of grains in any moment of time t after they are gripped by the rollers:

$$V = \frac{F_{mp}}{m}t + gt + V_0 \tag{5}$$

By integration of expression (5) we obtain a dependency for the determination of the value of the movement performed by grain in a certain moment of time:

$$l = \frac{F_{mp}}{m}t^2 + \frac{gt^2}{2} + V_0 t + l_0 = t_2(\frac{F_{mp}}{m} + \frac{g}{2}) + V_0 t + l_0 \tag{6}$$

The initial movement $l_0 = 0$ since in the accepted coordinates point B is the starting point of accounting on the axis OZ of the grain movement in the working area of the crusher. Proceeding from the assumption that in equation (6) the value $(\frac{F_{mp}}{m} + \frac{g}{2})$ is constant for any batch of grain and a definite design of a crusher, this value, for better clarity, can be designated as constant A, i.e. $A = (\frac{F_{mp}}{m} + \frac{g}{2})$.

After such a substitution expression (6) is written in the following way:

$$l = At^2 + V_0 t + l_0 \tag{7}$$

Considering already definite limitations

$$0 \le V_0 \le V = \omega R,$$

$$l_0 = 0$$
$$l_{max} \le \sqrt{R(S_0 - S)},$$
$$A \ge 0,$$

and that counting of the time t and the path l covered by grain in the crushing area starts at point B of its grip by the rollers, the total graphic dependence l on V_0 and t can be reflected as follows (Fig. 3).

The analysis of graphic dependencies (Fig. 3) indicates that in case grain is introduced into the working area of the first-stage crushing at the velocity $V_0 = V_6 = \omega R$, minimum time t_{min} is required for grain to pass the section of the working area of the first-stage crushing $l_{max} = (BC)$. This means that on condition the grain delivery from the feeding hopper 3 (Fig. 1, a) is uninterrupted and uniform a maximum amount of grain will pass the working area and will be crushed during a certain interval of time. Minimum time for grain to pass the working area of the first-stage crushing ensures maximum throughput capacity, or efficiency, of the crusher.

Experimental investigations have been conducted into the impact on the efficiency and energy intensity of the crusher, caused by rotation frequency of the blade-type feeding roller, which is the basic factor that determines the value of the feeding velocity of grain into the working area of the first-stage crushing if the height of its fall from the blade of the feeding roller to the point of grip and air resistance during this fall are ignored. Investigations were carried out with barley grain at 18 %

moisture content, crushed in an experimental two-stage grain crusher having rollers for crushing with a 275 mm diameter and rotational velocity $V_в = 6.5$ m·s^{-1}. The outer diameter of the blade-type feeding roller $d_n = 135$ mm, its length – 400 mm, the number of blades – 12. The rotation frequency varied within a range $n=5...15$ s^{-1}, which corresponds to the initial velocity of grain $V_0 = 2.1...6.5$ m·s^{-1}. On the basis of the results of the experimental research of the present crusher, graphic dependencies have been built (Fig. 4).
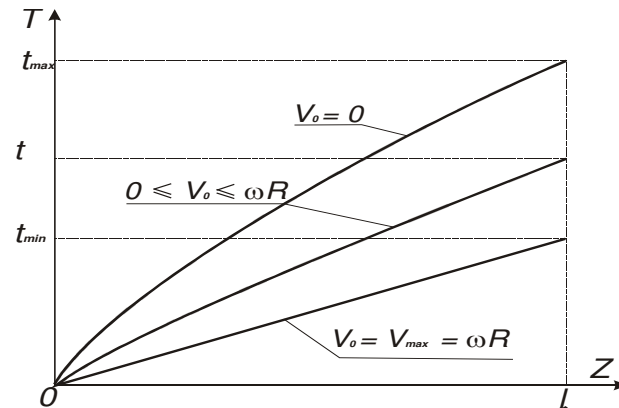

Fig. 3. **Value of the movement of the grain mass in the working area of the first- stage crushing, depending on the time t and velocity of its transfer into the working area V_0**

Increasing the rotation frequency n (and, consequently, the feeding velocity of grains into the working area of the first-stage crushing), using a blade-type roller as a feeding device, results in increased efficiency (the throughput capacity) from 3.2 to 4.4 t·h^{-1}, the consumption of energy falling from 4.6 to 3.6 kWh·t^{-1}, which confirms the results of theoretical studies – the crusher operates more efficiently. Efficiency Q of the crusher reaches its limit at the feeding velocity V_0 which is a little less than the rotational velocity V_0 of the rollers for crushing. Evidently, this is connected with elements of clumping that arise at high velocities of the grain mass at the entrance into the working area (point B – Fig. 2) since the velocities of individual grains in the flow are not equal – some of them have higher velocities than the rotational velocity of the rollers for crushing $V_в$. Energy intensity E of the crushing process is in inverse dependence on the efficiency Q and practically repeats the form of its curve: energy intensity is the lowest at the highest efficiency of the crusher.
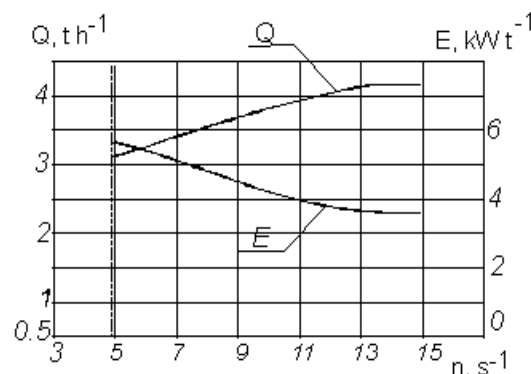

Fig. 4. **Impact of rotation frequency of the blade-type feeding roller upon the indicators of the performance of the crusher – its efficiency Q and specific energy consumption E**

Conclusions
1. Theoretical research of the movement of grain in the working area of the first-stage crushing showed that in case its feeding velocity into the working area is equal to the linear velocity on the working surfaces of the rollers for crushing, minimum time is required for grain to pass the first stage of crushing. Correspondingly, at this velocity of feeding the two-stage crusher will operate with maximum efficiency.

2. The conducted experimental investigations confirm for the most part the theoretical research: increase in the feeding velocity of grain into the working area of the first-stage crushing raises the efficiently of the crusher: its efficiency increases when the energy intensity of the process is decreased but it reaches its highest value at the feeding velocity of grain which is by 1.5...2 m·s^{-1} lower than the rotational velocity of the rollers for crushing. This is connected with elements of clumping that arise at high velocities of the grain mass at the entrance into the working area. Specific energy intensity of the crushing process is in inverse dependence on efficiency.

References

1. Guritno,P., Haque, E. Relationship between energy and size reduction of grains using a three-roller mill. Transactions of the American Society of Agricultural Engineers. Issue 4, July 1994, Pages 1243-1248
2. Vaculik, P., Maloun,J., Chladek, L., Poikryl, M. Disintegration process in disc crushers Research in Agricultural Engineering. Volume 59, Issue 3, 2013, Pages 98-104
3. Сысуев В.А., Алёшкин А.В., Савиных П.А. Кормоприготовительные машины. Теория, разработка, эксперимент: (Feed Preparation Machines. Theory, Development, Experiment.)– Киров: НИИСХ Северо-Востока, 2009. – Т. 2. – 496 с. (In Russian).
4. Рекомендации по заготовке и использованию высоковлажного фуражного зерна (Recommendations for the Preparation and Use of Forage Grain with High Moisture Content) / В.И. Сыроватка, В.Д. Попов, В.А. Сысуев и др.:, под редакцией Ю.Ф. Лачуга. – М.: Россельхозакадемия, 2006. – 130 с. (In Russian).
5. Патент 2399420 RU МПК В 02С. Вальцовый станок (A Roller Mill). Опубл. 20.09.2010, Бюл. №26. – 5 с. (In Russian).
6. Патент RU № 2477178 С2 МПК В 02С 4/06 Способ плющения фуражного зерна и устройство для его осуществления (A Method for Crushing Forage Grain and Device for Its Implementation) / Сысуев В. А., Савиных П. А., Казаков В. А. и др. Бюл. № 7, 2013 г. (In Russian).
7. Марсов В.И., Славуцкий В.А. Автоматическое управление технологическими процессами на предприятиях строительной индустрии (Automatic Control of Technological Processes at the Enterprises of Building Industry). Стройиздат, Ленинградское отделение, 1975, 287 с. (In Russian).
8. Андрианов А.М. Распорные усилия при плющении зерна валками // Совершенствование технологий и технических средств уборки, обработки и переработки зерна (Spacing Forces during Grain Crushing by Rollers // Improvements in Technologies and Technical Means for Harvesting, Treatment and Processing of Grain). Сборник научных трудов Воронежского СХИ им. К.Д. Глинки. – Воронеж, 1990. – С. 176-183. (In Russian).
9. Андрианов А.М., Елисеев В.А. Влияние окружной скорости и диаметра валков на производительность и удельный расход энергии зерноплющилки // Механизация сельскохозяйственного производства (Impact of the Rotational Velocity and Diameter of Rollers upon the Efficiency and Specific Consumption of Energy by Grain Crushers// Mechanisation of Agricultural Production). Записки Воронежского СХИ им. К.Д. Глинки. – Воронеж, 1972. – Т. 53. – С. 154-158. (In Russian).