Research results of cutting horticultural raw material using chip slicer with a zigzag knife in reverse direction

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Abstract. The general view and description of the operation of a chip slicer for horticultural raw material is presented. Theoretical studies of the cutting process using the proposed device are carried out, with an adequate obtained mathematical, which includes the geometrical description of the interaction between the raw material and the proposed cutting device, with its algorithm created in a computer program. An experimental sample of a chip slicer for horticultural raw material, as well as that of a cutting device (a zigzag knife wall with the straight or reverse knife location) is developed and produced. The cutting forces are experimentally determined, depending on the geometrical parameters of the cutting device. The positive effect of using the cutter is a decreased energy consumption of the process, as well as the minimum destruction of the structure of the raw material processed, and high productivity.

1. Introduction
Cattle breeding is a very important branch of agriculture, which influences its economical development to the greatest extent. The insufficient quality of foods limits the possibility to implement a range of potential capabilities of the animals, namely: the necessary nutrition level, a scientifically reasoned ration structure, and the necessary contents of nutrients are not maintained. The use of tuberous roots in nutrition allows to introduce the necessary amount of sugar and farina into the rations of agricultural animals, thus increasing the productivity and quality of the products obtained.

Thereby, a large spread of the physical and mechanical properties of the foods limits the continuous operation of the machines without any need arising to reconfigure them, whereas the difference in slicer designs testifies that the process carried out has been studied insufficiently.

The analysis of the parameters and designs of the tuberous root slicers demonstrates that the machines produced in a standard way are metal-intensive, have low values of chipping quality, high energy consumption during the operations, and the main thing is that they do not always meet the modern zoocultural requirements [1].

An important task of the agricultural production and processing industry [2], in particular, in increasing the efficiency of snack production, is an increase in the mechanization level of the operating procedures and minimizing the energy consumption at the most energy-intensive section of a chip production line, i.e., at the one of chipping horticultural raw material into slices [3-5]. When chips are
produced, a number of fat oxidizing processes and undesirable formation of carcinogenic substances take place, which have adverse effect on human health. Besides, a high mass fraction of oil in the finished products causes racidification and a decrease in the qualitative parameters of the product followed by a decay of the whole contents of a package. It appears from this that the homogeneous residual moisture of the material is reached by the equal thickness of all slices. Thereby, equal conditions are created when heat treatment of the material is performed, with obtaining products, which would possibly be uniform in oil content.

To reduce the power consumption during the operation of cutting apples and potato tubers into slices for the agriculture and processing industry, we propose a slicer (Figure 1).

![Figure 1](image_url)

**Figure 1.** Chip slicer for horticultural raw material: a – chip slicer for horticultural raw material, overall view; b – chip slicer for horticultural raw material, top view, c – knife wall, side-view, d – knife wall, top view A-A, e – knife wall, bottom view; 1 – body, 2 – frame, 3 – chipping chamber, 4 – loading throat, 5 – discharge window, 6 – discharge container, 7 – gear motor, 8 – drive shaft, 9 – crank, 10 – adjusting nut, 11 – piston-rod, 12 – knife wall, 13 – knives, 14 – upper plate, 15 – lower plate, 16 – central knife block, 17 – lateral knife block.

The slicer operates as follows. The material to be processed gets into chipping chamber 3 through loading throat 4. Knife wall 12 moves along the guideways (not shown in the figure) inside frame 2 towards stationary shear prop 18 by means of transmitting the turning torque by drive shaft 8 from gear motor 7 to crank 9, through piston-rod 11. The horticultural material gets through knife wall 12, being chipped into slices with the necessary thickness and removed through discharge opening 5 into discharge container 6. Thereby, the tips of shear prop 18 come into the cavities of the knife wall and that results in complete chipping of the whole material, which is in chipping chamber 3, with an increase in productivity.

To reduce the energy consumption in the cutting process, we have developed a design of a zigzag knife wall with a turned knife location, which contributes to a reduction in the tangential consituent of the cutting speed and a uniform distribution of the forces on the upper and lower plates of the knife wall.

### 2. Mathematical modeling

The research assumes that fruits or tubers, which are meant for processing on the slicer proposed, pass a strict inspection and have nearly equal dimensions and their form is close to the ideal. This allows not to consider the influence of the material form on the cutting process, nor to study the dependence of the
forces on the fruit or tuber dimensions. Thus, a real fruit or tuber is replaced with a ball with preset radius $\rho$ in the model. 

The forces, which affect the material in the cutting process, are combined from the interaction between the knife block, the force on the part of the prop, and the force of gravity. The latter is negligible in comparison with the cutting force. The motion pattern of a fruit or a tuber when it is pressed down to the knives by the prop also allows neglecting the dynamic effect by considering the motion as quasistatic. However, by confining ourselves to the study of the forces, which are necessary to apply on the part of the installation drive, and the energy spent on cutting, it is expedient to consider the only one quasistatic equation, the equation of the forces along the longitudinal axis of the slicer, according to which the force on the part of the drive will be determined by the joint interacting forces between a fruit or a tuber and the knife block in the projection on the longitudinal axis of the slicer (Figure 2).

\[ P_x = \sum P_{i,x} \]  

where $P_x$ is the force applied on the part of the installation drive, $N$; $P_{i,x}$ are the interacting forces between a fruit and the knife block, $N$.

Assuming that the center of a fruit or a tuber passes in between the parts of the block when the material is pressed through the knife block (figure 3a), we can believe that each $i$-th knife cuts a slice with the radius of
\[ \rho_i = \sqrt{\rho_i^2 - \left(\frac{D - D_2}{2}\right)^2} \]  \quad (2)

where \( D \) is the distance between the axial lines of the blades of the neighbouring knives, \( m \); the numeration of the knives goes from the center to the edges in both directions (in figure 3a, three knives are nominally set out on the right).

Coordinate axis \( x \) is introduced for each fruit or tuber, along the longitudinal axis of the slicer, with its point of reference being set at random, from considerations of convenience. The coordinate of the fruit center is denoted through \( x \) (without indices) when it moves through the knife block. The coordinate of point \( A_s \), the intersection point of the axis, and the cutting edge of an \( i \)-th knife, is denoted through \( x_s \). Knife angle \( \tau \) is determined through angle of pinching \( \theta \) as:

\[ \tau = \frac{(\pi - \theta)}{2} \]  \quad (3)

Then the depth of penetration of blade \( b_i \) in \( i \) section (figure 3b) is determined by equation:

\[ b_i = \rho_i - (x_i - x)\cos \tau \]  \quad (4)

the length of a cut along the cutting edge of a knife is given by:

\[ \rho_i^f = 2\sqrt{\rho_i^2 - (x_i - x)^2 \cos^2 \tau} \]  \quad (5)

and along the backside of a knife:

\[ \rho_i^b = 2\sqrt{\rho_i^2 - ((x_i - x)\cos \tau + H)^2} \]  \quad (6)

where \( H \) is the knife width, \( m \).

Depending on values \( i \) and \( x \), the subradical expressions in formulas (2), (4), (6) or expression (5) can appear to be negative. In this case, the respective value, which is determined by the formula, is accepted as equal to zero.

The distance along \( x \) axis between points \( A_i \) and \( A_{i+1} \) determines the knife shift and is denoted through \( \Delta \). If \( \Delta \geq H / \cos \tau \), the knives do not overlap each other (figure 4a) and do not virtually have mutual influence on the cutting process – a slice cut only interacts with a single knife at each moment of time. However, such location significantly increases the depth of the knife block and that is not always acceptable. Therefore, it is usually \( \Delta < H / \cos \tau \); there are areas of knife overlap (figure 4 b), where a slice is subjected to a proportional increase in deformation, which, in case of a linear model of the elastic properties of a fruit or tuber material, results in a respective increase in the forces of compression and friction. To take this effect into account, a dimensionless coefficient of knife overlap is introduced, which is determined by the formula

\[ \lambda = 1 - \Delta \cos \tau / H \cdot \lambda \in [0,1] \]  \quad (7)

If the value of coefficient \( \lambda \), which is calculated under formula (7), appears to be negative, the coefficient is equated with zero.
Each blade is considered to be two-edged in general, with different sharpening angles $\beta^r$ and $\beta^l$ on the right and left respectively. The inclination of the knives under angle $\tau$ relative to the perpendicular line to the cutting direction enables a kinetic transformation of the blade sharpening angles, which, as it is shown in the study, is described by the formulas

$$
\beta_r = \arctg (\tan \beta^r \cos \tau)
$$
$$
\beta_l = \arctg (\tan \beta^l \cos \tau)
$$

(8)

where $\tau$ is the blade (sliding) angle, deg.

3. The materials, methods, and results of experimental studies

The experimental studies of the zigzag knife wall of the chip slicer for horticultural raw material (figure 5) were directed to determine the rational values of the geometrical parameters of the cutting device in order to minimize the energy consumption.

To achieve the goal set, the character of the process was studied and the maximum cutting force for apples was measured with the following knife configurations for straight and turned knife location (figure 6). To study the load characteristics of cutting, a portable system was used, including strain sensors [6], a power supply, an analog-to-digital converter (ADC/DAC), as well as a notebook with specialized software. Also, when cutting devices of slicers for agricultural raw material are calculated, it is necessary to consider the physical and mechanical parameters of the latter [7], including the rheological properties.
Figure 6. Cutting options: (a) width, 3 knives, depth, 2 knives; (b) width, 5 knives, depth, 3 knives; c – width, 7 knives, depth, 4 knives.

The results of the researches to determine the maximum cutting force are set out in figure 7a.

It is found out that an increase in the geometrical parameters of the zigzag width and depth results in a reduction in the force by 40-51% in any cutting options, which corresponds to the following values of the cutting force: 2.27-4.18 kN/m when the knives are located in a straight way and 1.9-3.18 kN/m when they are turned.

Besides, the turned knife location in the zigzag knife wall results in a reduction in the cutting force by 16.2-29% in any cutting options, as, when the width/depth = 3/2; the straight knife location allows to achieve the cutting force of 4.48 kN/m, and the turned location does 3.18 kN/m.

The results of the research of how the vertical shift of the knives relative to each other influences the power and qualitative parameters of cutting are set out in figure 7b.

Figure 7. Results of studies of the energy data of the chip slicer for horticultural raw material: (a) results of the study of the influence of the knife configuration in the wall on the cutting force; (b) results of the study of the influence of a vertical knife shift on the cutting force; (c) results of the study to determine the influence of the angle of pinching by the knives on the cutting force (where ∆≥11 mm).
Altogether, a vertical knife shift in the zigzag knife wall for more than 11 mm allows to reduce the total cutting force by 25-28.7 %, however, with the increase in the value of this geometrical parameter, the force does not change or it decreases slightly, which allows to draw a conclusion about a rational value of the shift of 11...13 mm.

To carry out the studies of how the angle of pinching influences the cutting process, the maximum force was recorded at various options of the knife location in the central and lateral segment of the knife wall, where the turned location formed an angle of pinching. Thereby, the angles of pinching by knives are formed by the turned knife location in the central and lateral segments of the knife wall. The angles of pinching obtained, namely: 120, 130, 140° (Figure 7c), correspond to the angles of cutting with gliding of 30, 25, 20°, these data being established as a result of experimental researches.

It is established that a reduction in the angle of pinching reduces the cutting force. As it is clear from figure 7c, the use of the angle of pinching of 120° allows reducing the cutting force by 13.6-20.8 %. Such an effect is conditional on a decrease in the frictional forces by means of reducing the knife contact area in the different segments of the cutting device.

4. Conclusions
The theoretical studies carried out of the cutting process of horticultural raw material by an automated rotor slicer allow simulating the operating procedures for developing and substantiating similar technical means.

An increase in the width and depth of the zigzag in the cutting device of the chip slicer for horticultural raw material results in a reduction in the energy consumption by 40...51 %, which corresponds to the following values of the cutting force: 2.27-4.18 kN/m when the knives are located in a straight way and 1.9-3.18 kN/m when they are turned. The turned knife location in the zigzag knife wall results in a reduction in the cutting force by 16.2-29 % in any cutting options; thus, when the width/depth = 3/2 with the straight knife location, the unit cutting force is 4.48 kN/m, and it is 3.18 kN/m when the location is turned. A positive effect is reached by decreasing the friction force of the product along the knife blade by means of reducing the contact area of the knives in various planes and segments of the cutting device. Also, the turned knife location excludes the turning torque and forced motion of the material processed towards the walls of the working chamber by reducing the friction force and, hence, the cutting force.

As a result of the researches carried out, methods and algorithms of calculation have been developed, which allow qualitatively assessing the dynamic condition of the material processed and this enables to analyze the condition of the equipment proposed and achieve the rational design parameters and operating modes.

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