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MOTIONAL CHARACTERISTICS OF GRAINS IN THE MULTI-HOLE SPACE OF A MULTI-DISC GRINDER

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Abstract

It was investigated multi-disc grinders in directions knowledge of, describe and utilize, for design and structural purposes, the characteristics that indicate the relations between speeds, idle movement, loads and the indicators of motion variables in the grinding space. The mathematical description of the states of and changes in grains, their surface and volume during movement (idle and working movement) of the components and assemblies in the multi-hole grinding process was obtained as a objective of this work.

Keywords: biomass grinding, square of quasi-cutting, working elements geometry

1. Introduction

Investigations into multi-disc grinders demonstrate that it is possible to acquire knowledge of, describe and utilize, for design and structural purposes, the characteristics that indicate the relations between speeds, idle movement, loads and the indicators of motion variables in the grinding space.

The objective of this work is to provide a mathematical description of the states of and changes in grains, their surface and volume during movement (idle and working movement) of the components and assemblies in the multi-hole grinding process.

2. Motional Characteristics

Usable characteristics and multi-disc and multi-hole grinding outcome variables: power demand (P_R=f(n)), degree of fineness (λ=f(n)) and mass target efficiency (Q_m= f(n), $Q_c \leq Q_m$) depend on the common area of the edges of two holes (S_c,S_T), density and volume of grain in the working space (ρ_m,V_g), rotational, angular and linear speed of a component and time (n,ω,v,Θ,t_i) - $L(P_R,\lambda,Q_m,Q_c)=P(S_c', S_T, \rho_m^{m+1}, V_g, n,\omega,v,\Theta,t_i)$; they also depend on the volumetric dosing of mass feed q(0;1).

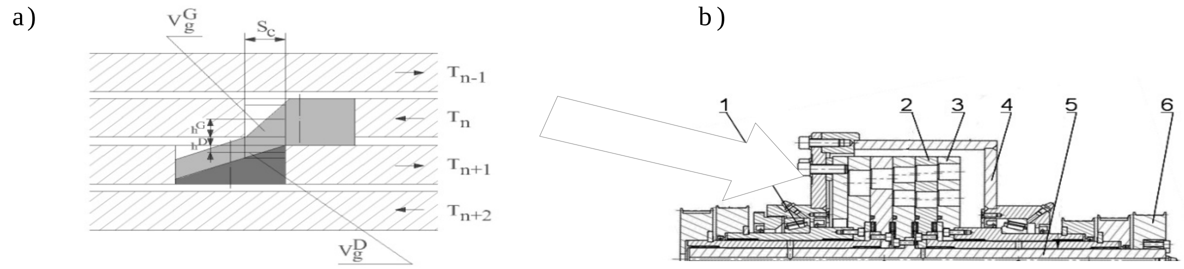

Fig.1. RWT-5KZ multi-hole five-disc grinder working unit, [8,9]: a) grain filling in two adjoining working holes of the quasi-cutting unit: T_{n-1} do T_{n+2} – subsequent grinding discs, h^G – height of material column before the cutting plane, h^D – height of material column behind the cutting plane, V_g^G – calculated volume of material before the cutting plane, V_g^D – calculated volume of material behind the cutting plane, S_C – common area of the quasi-cutting pair of holes; b) cross-section of the multi-disc unit: 1 –bearing, 2 – grinding disc (so-called „preceding” disc), 3 – grinding disc (so-called "subsequent" disc), 4 – body, 5 – shaft, 6 – pulley

The usable characteristics of grinding, dependent on the movement of grain and grinder components were named the motional characteristics of grain [1,2,7-11].

Assumptions: To determine motional characteristics of grain, two states were assumed which are dependent on the linear speed of the grinding holes edges (Fig. 1) [7,11]: the first one – idle state, involving only movement and mixing, exclusive of grinding (linear speed of points on edges – below $0.7 \mathrm{m \cdot s^{-1}}$), second – working state, with significant grinding initiators (above $0.7 \mathrm{m \cdot s^{-1}}$). The characteristics have been formulated applying the following assumptions [1,2,7,11]:

a) the number of contacts between grains, components and particles along their pathway influences the quality and grinding effects,
b) the positioning of holes in respective discs of the grinding unit forms a line in the internal cone that starts on the initial diameter (d) with the pitch (s) and the length of the helical line (c), which increases by the thickness (g) and the number of discs (n) up to the length (C) – finished with an external cone of the hole edges,
c) movement, mixing and grinding of grains (p-m-r) depend, among other things, on friction conditions, structural features of discs and the positioning of holes in discs, with dynamic movement of the machine structural components and of grain ($p=p_m+p_z$) occurring during idle movement and when working load is applied to the machine ($p_m=p_j+p_r$), and of grains ($p_z=p_o+p_p$) during axial and radial movement within the hole and disc space,
d) during movement and mixing of grain (p-m), apart from following trajectory similar to the helical line (original path), grains also rotate around the centre of gravity (secondary movement); grinding dynamics does not rule out both types of movement (r),
e) grinding on the edges of holes between adjoining discs is performed through equally split quasi-cutting,
f) cross-section of holes in discs is dependent on the outflow and can be described using Kvapil's theory [5]:

$$S_{\min} = K \cdot n \cdot (5 \cdot d_z)^2$$

where: S_{min} – the smallest cross-section of the hole through which grain is freely moved – m^2, K – experimental coefficient (for corn grains K=1,4), n – coefficient for the shape of holes in discs, for round holes n=0,85, d_z – average size of grain – m.

In both states of component movement, in particular in the second one – depending on the shape of grain and tools (holes) and the positioning of their cutting edge in relation to the movement direction – some of the edges perform the cutting, other scratching operations and yet other the cutting of grooves in grains. Hence, what we see here is dynamic, complex and volumetric intensity of grinding per path unit. On assuming fixed reference values expressed in coefficients, grinding intensity can be expressed applying the following dependency:

$$I_{DR} = \frac{U}{L \cdot P} = c_{DR} \cdot \frac{N \cdot d \cdot x}{H \cdot y}; \frac{dm^3}{m \cdot W} \tag{1}$$

where: *U*- volumetric loss of grain in dm^3, *L*- path (p-m-r) in m, $P=P_j+P_R$ – power supplied to the system to defeat resistance to idle and grinding motions in W, *N* – normal unit load in MPa, c_{DR} – factor of proportionality in $dm^2 \cdot m^{-1} \cdot W^{-1}$, *d* – substitute height of the cutting edges measured perpendicularly to the motion direction in m, $x=(i_{lkr}/i_{lzk})$ relation between the number of cutting edges and the total number of grains and edges on motion trajectory, *H* – grain hardness, *y* – coefficient characterising relative number of grains and holes edges in transferring discs ($C_{kR}(S_e, S_T, V_z)$), susceptible to load ($y=f(C_{kR})$).

The positioning of grains being ground in the working space of a multi-hole grinder (Fig. 1a) is described by statistical distribution of its length. Because the material present in the holes of this same disc is characterised by the same particle size ρ and is subject to the same grinding and cutting process in each hole, its state for the purpose of this analysis is indexed with the cutting number (*m*) and the disc number (*n*) [7,8]:

$$\rho_n^m : [0, l_{\max}] \rightarrow [0,1], \qquad \int_0^{l_{\max}} \rho_n^m \, dl = 1. \tag{2}$$

The thickness of the *n*-th disc, for the purpose of this analysis, is marked with the symbol y_n, and the height up to which the material fills the hole in the *n*-th disc prior to the *k*-th cut by the symbol $\tilde{y}_n^{(k)}$.

In efficient grinding and cutting, length distribution of grains which filled the empty space in the (*n*+1)-th disc changes as per the following dependency (Fig.1a):

$$\tilde{\rho}_{n+1}^m(x) = A_{n,m}\rho_n^m = \left(1 - \frac{x}{y_{n+1} - \tilde{y}_{n+1}^m}\right)\rho_n^m(x) + \frac{1}{y_{n+1} - \tilde{y}_{n+1}^m}\int_x^{l_{\max}} \rho_n^m(l)\,dl, \tag{3}$$

while of those left in the *n*-th disc as per:

$$\tilde{\rho}_n^{m+1}(x) = \tilde{B}_{n,m}\rho_n^m = \left(1 - \frac{x}{\tilde{y}_n^m}\right)\rho_n^m(x) + \frac{1}{\tilde{y}_n^m}\int_x^{l_{\max}} \rho_n(l)\,dl, \tag{4}$$

where: A, B – scholastic operators for m-th cut, n-th disc.

It was assumed for simplification purposes that, subsequent to grinding, distribution of granulated product in the hole spaces of the (*n*+1)-th disc will be uniform (cut fraction and that present in the hole before cutting will mix) and it will therefore be the weighted average from ρ_{n+1}^k i ρ_n^k:

$$\rho_{n+1}^m(x) = \frac{\tilde{y}_{n+1}^m}{y_{n+1}}\rho_{n+1}^{m-1} + \frac{y_n - \tilde{y}_{n+1}^m}{y_{n+1}} A_{n,m}\rho_n^m(x) \tag{5}$$

During the modelling of the common part surface, integration of grinding momentary cross-section was employed [1,2,5]:

$$S_C = \int_{x_1}^{x_2} \left\{b_2 + \left[R_2^2 - (x-a_2)^2\right]^{1/2}\right\}dx - \int_{x_1}^{x_2} \left\{b_1 - \left[R_1^2 - (x-a_1)^2\right]^{1/2}\right\}dx \tag{6}$$

where:

a_1, a_2, b_1, b_2 - C_1 and C_2 hole centres coordinates
R_1, R_2 - holes radius vector.

Based on what has been said, distribution of grain length in ground material which filled the empty space of the (*n* + 1)-th disc changes as follows:

$$\tilde{\rho}_{n+1}^m(x) = A_{n,m}\rho_n^m = \left(1 - \frac{x}{h^D}\right)\rho_n^m(x) + \frac{1}{h^D}\int_x^{l_{\max}} \rho_n^m(l)\,dl \tag{7}$$

whereas in the material left within *n*-th disc in the following way (analogical reasoning):

$$\bar{\rho}_n^{m+1}(x) = \bar{B}_{n,m}\rho_n^m = \left(1 - \frac{x}{h^D}\right)\rho_n^m(x) + \frac{1}{h^G}\int_x^{l_{max}} \rho_n(l)dl \tag{8}$$

It must be remembered that the column of the material being cut is not the entire material that has been moved to the lower hole. Its volume is $S_c \cdot h^D$ whereas that of the entire material moved from the preceding hole to the subsequent hole is
$V_g^D(\alpha_c) - V_n^m$

It means that the second and third component in (8) must be multiplied by the relation between these volumes:

$$\bar{\rho}_n^{m+1}(x) = \bar{B}_{n,m}\rho_n^m = \left(1 - \frac{Sc \cdot x}{V_g^D(\alpha_c) - V_{n+1}^m}\right)\rho_n^m(x) + \frac{Sc}{V_g^D(\alpha_c) - V_{n+1}^m}\int_x^{l_{max}} \rho_n(l)\,dl \tag{9}$$

It was assumed for simplification purposes that, subsequent to cutting, the grain length distribution in the (*n*+1)-th disc will be uniform (cut fraction and that present in the hole prior to cutting will mix), and therefore it will be the weighted average from ρ_{n+1}^{m-1} and $\bar{\rho}_{n+1}^{m-1}$.

$$\rho_{n+1}^m(x) = \frac{V_{n+1}^m}{V^D}\rho_{n+1}^{m-1} + \frac{V^D - V_{n+1}^m}{V^D}\bar{B}_{n,m}\rho_n^m(x) \tag{10}$$

The filling level of the quasi-cutting unit and thus the efficiency of the cutting process depend on the value of the function V^D, V^G and S_c which in turn depend on the direction of the effective gravitation and on the total volume of material in both holes before cutting
$(V_{n+1}^m + V_n^m)$.
Other indicators of variables are provided based on tests.

Intensity is the measure of the reduction of initial volume of grains (V_g) on the way from the entrance to the exit from a multi-disc unit, per unit of power consumed by the grinding drive system. The first state of multi-disc grinding, where only movement and mixing (v_R<0,7m·s^{-1}) occur, does not result in explicit volume reduction (U), however, grinding elements travel a specific path (L) and the system is supplied with power (P_j). After efficient speed is exceeded (v_R>0,7m·s^{-1}), volume reductions are observed resulting from the effects of the cutting edges with grinding power (P_R) on the path (L). Dynamic intensity of grinding is directly proportional to the unit load (N) and inversely proportional to the grain hardness (H) and the conditions of the grinding unit ($C_{kR}(S_c, S_T, V_g)$,C_k). The interpretation of the grinding mechanism should be that a grain with the area *S*, being moved between the edges of a grinding element, pressed using axial force *N*, is deformed elastically and plastically by the width *b*, becoming swollen over the volume of the front surface. After the load is removed, deformations are reduced by the value of elastic deformations to σ_1. Assuming that the nature of elastic deformation is analogous to that resulting from ball indentation, a different formula is obtained for grinding intensity:

$$I_{DR} = n \cdot d_z^3 \cdot \left(\frac{1}{\sigma} - \frac{1}{\sigma_1}\right) = k(\mathrm{S_c}, \mathrm{S_T}, \mathrm{V_g}) \cdot \frac{N}{E}; \frac{dm^3}{m \cdot W} \tag{11}$$

where: *n* – number of grains carrying normal load N, d_z – grain diameter in m, *k* – factor of proportionality taking account of the relations between momentary volumes, surfaces and power, in $m^3 \cdot m^{-1} \cdot W^{-1}$, *E* – coefficient of elasticity (tensile modulus) in MPa.

Because it is difficult to precisely determine elastic and plastic deformations for grains in accordance with (11), and the grinding intensity is determinable by complex physical and mechanical processes, path and power for grinding is calculated or determined based on measurements.

Similarly, in modelling and identification of grinding with regard to grain in motion as per the dependency (1), in particular with regard to movement and mixing of grains, the effect of internal friction must be taken into account. The assumption no. b indicates that movement, mixing and grinding involves the friction and helical trajectories, in the space described by two radial lines: $L=C\text{-}c$ (between external and internal edges of holes in discs, e.g. along the spiral of Archimedes with the polar equation: $r=a\varphi$) and thus:

$$I_{DR} = \frac{U}{L \cdot P} = \frac{U}{\lambda \cdot v_{p^*m} \cdot t_{p^*m} \cdot P}$$

or (12a and 12b)

$$I_{DR} = c_{DR} \cdot \frac{N \cdot d \cdot x}{(C-c) \cdot P} = c_{DR} \cdot \frac{N \cdot d \cdot x}{\left(\sqrt{\pi^2 \cdot D^2 + s^2} - \sqrt{\pi^2 \cdot d^2 + s^2}\right) \cdot P}; \frac{dm^3}{m \cdot W}$$

where: λ – coefficient determining the effect of internal friction (μ_w) on the grain movement speed (v_{p+m}) in the t_{p+m} time of passage through the multi-disc unit:

$$\lambda = \frac{1}{\sqrt{2\mu_w\left(\frac{1}{\mu_w} + 2\mu_w\right) - \sqrt{1+\mu_w^2}}},$$

D – outer diameter of the helical line on which the holes are positioned in m, d – inner diameter of the helical line on which the holes are positioned in m, s – pitch equal to disc thickness – m.

It was assumed in the experimental verification that the trajectory of grain moving in the area between the radial lines of the external and internal cone (holes positioning envelope) is a continuous line – in terms of movement and mixing (first state) and continuous and disrupted (for the duration of grinding) – in the case of the second state (efficient edge speed, for e.g. corn: $v_R > 0{,}7 m \cdot s^{-1}$). As the speed of grains during movement and mixing is low and because grains are stopped for the duration of quasi-cutting and there is a potential increase in the flying movement of grain specks as a result of bouncing subsequent to grinding, it can be assumed for simplification purposes that the second state has the motion trajectory and time equal to $t_{p+m+r}=t_{p+m}$.

Idle movement characteristics: Characteristics that are identical for states and changes in all multi-hole spaces of multi-disc grinding units are variable power demand $P_{Rj|m}$ depending on the rotational speed of units and grinder components n_m (machine idle running characteristics) – without ground material:

$$P_{Rj|m} = f(n_m), q(0) \tag{13),}$$

which, depending on the linear speed of a grinding element $v_{\bar{R}}$, takes the following form:

$$P_{Rj|m} = k_{1m} \cdot v_{\bar{R}}, \text{ for: } q(0), Q_m = 0, \ Q_c = 0 \tag{13a}$$

Similarly, power $P_{Rj|(m+z)}$ for machine idle movement with grain (feeding with grain q, movement of machine components and grain with the speedn_{m+z}, without grinding):

$$P_{Rj|(m+z)} = f(n_{m+z}), q(0;1) \tag{14),}$$

which leads to the dependency that takes into account the volume of grain $V_{\bar{g}}$ in material moved between discs:

$$P_{Rj|(m+z)} = k_{2(m+z)} \cdot v_{\bar{R}} \cdot f(V_{\bar{g}}), \text{ for: } q(0;1), Q_m = \frac{dm}{dt}, \ Q_c = 0 \tag{14a}$$

Dependencies from (13) to (14a) require tests to be conducted to determine idle movement modules and calculate moved material functional volume:

$k_{1m}, k_{2(m+z)}, f(V_{\bar{g}})$

Thus, we obtain the model of power dependency for machine components movement, with or without grain feed – without grinding operation (only grain movement), on the rotational speed, at zero or constant power supply, without grain size changes, without grinding efficiency, at target efficiency equal to zero ($Q_c=0$) but with movement efficiency or efficiency equal to power supply, without grinding operation $Q_m = \frac{dm}{dt}$. The characteristic of idle running is a special type of load characteristics. It corresponds to the mixing power characteristics ($P_R = P_m$).

Load movement characteristics: For different rotational speeds of discs (linear speed v_R on the radius vectors of the pass-through and grinding holes edges) and variable power supply/grain feed q(0;1), variable degrees of fineness, mass and target efficiencies (loads with full grinding) and totally different mass Q_m and target Q_c efficiencies (of a product specified in terms of size and geometry) are obtained.

Power utilised for grinding includes components of idle and grinding loads and of dynamic increase – depending on phenomena complexity:

$$P_{Ro} = P_{Rj(m+z)} + P_{Rr} + P_{Rd}, \quad \text{for: } q(0;1),$$
$$\text{and for } \lambda = f(n, \Delta n) \neq 1, Q_m = f(n, \Delta n) = \frac{dm}{dt}, \ Q_c \neq 0 \qquad (15),$$

Below is a proposed experimental description of power input under load relative to cross-sections of grain mass in grinding holes S_c and on the intra-disc surfaces S_T, in the form of a general dependency, dependent on the speed of the grinding edge [9]:

$$P_{Ro} = \left(k_{2(m+z)} \cdot f\left(V_{\bar{g}}\right) + \tau \cdot f\left(S_c, \bar{\rho}_n^{m+1}, V_{\bar{g}}\right) + \varepsilon_d \cdot \tau \cdot f\left(S_c', S_T, \bar{\rho}_n^{m+1}\right)\right) \cdot v_R \qquad (15a)$$

Dependencies (15) and (15a) require tests to be conducted to define dynamic increase module and calculate probable cross-sections participating in material grinding:
$\varepsilon_d, S_c, S_T, \bar{\rho}_n^{m+1}$

3. Indicators analysis results

In order to determine the characteristics of idle running $(k_{1m}, k_{2(m+z)}, f(V_{\bar{g}}))$, load $(\varepsilon_d, (S_c, S_T, \bar{\rho}_n^{m+1}))$, efficiency $Q_m - \frac{f(\bar{\rho}_n^{m+1}, S_c, S_T, V_{\bar{g}}, n, \Delta n_{ij})}{v_R} -> max$ and unit power consumption $E_j = \frac{P_R(\bar{\rho}_n^{m+1}, S_c, S_T, V_{\bar{g}}, n, \Delta n_{ij})}{Q_m(\bar{\rho}_n^{m+1}, S_c, S_T, V_{\bar{g}}, n, \Delta n_{ij})} => min$, power demand of a five-disc grinder was tested in the cutting operation, both with and without ground material. In this work, an analysis was conducted to determine substitute function F_r (Fig.2), which takes into account the complexity of $F_r = f(S_c', S_T, \bar{\rho}_n^{m+1}, V_{\bar{g}})$. Sample results are presented in figure 2.

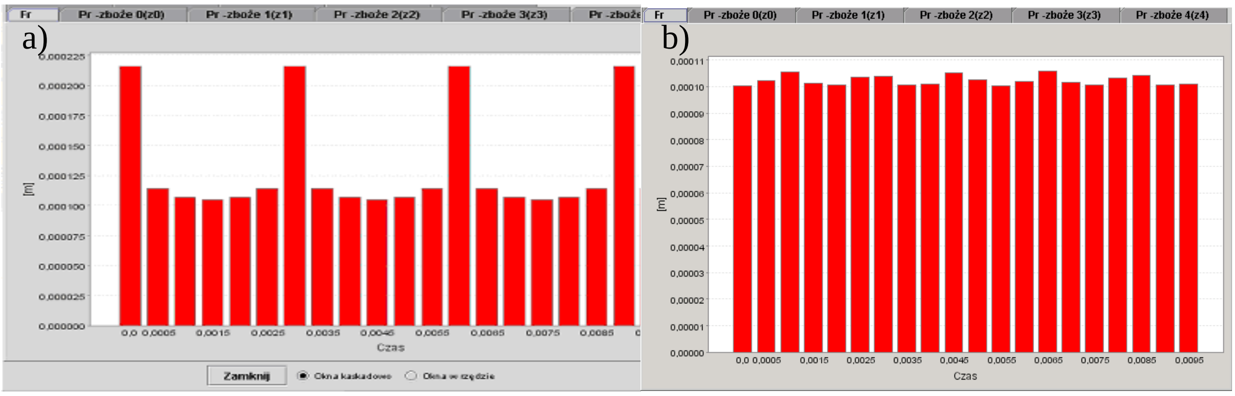

Fig. 2. Momentary function of F_r cross-section substitute function, dependent on the surface and volume of the adjacent working holes in discs $S_c', S_T, \bar{\rho}_n^{m+1}, V_{\bar{g}}$, for a) increase in the number of holes between discs PLOT= 2, b) PLOT=1

Active power P, consumed depending on the number of holes, angular speed of discs and under conditions of the programmed feeding of triticale, maize and rice grains (working movement, under load) are shown in figure 3.

The power demand function (Fig. 3 - mathematical description of states and changes of grinding power) obtained from a statistical analysis, movement of the multi-hole grinding components and units in the triticale and rice grinding process demonstrate percentage compliance of model and process response: Q=$\|14,7\|$. On the other hand, in the case of maize, quality function reaches on average slightly lower percentage compliance of results: Q=$\|19,2\|$.

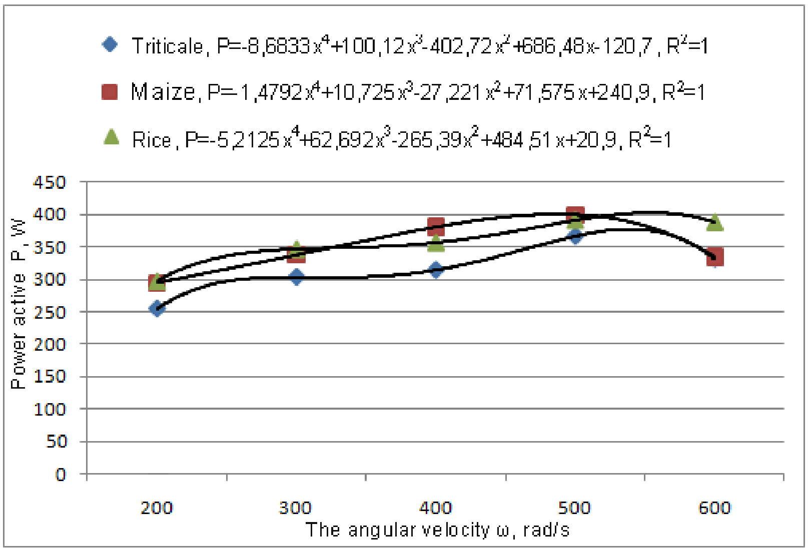

Fig 3. Active power consumed by drive units (P_j) utilized for the grinding of triticale, maize and rice grains, depending on the angular speed [8]

The results of machine tests of the grinding process were also estimated with momentary characteristics of their surface and grinding volume (e.g. as per Fig. 2). Here too the quality function reaches relatively high values as far as the model's quality estimator is concerned, which indicates that there is significant discrepancy between the response of the model and the actual object: Q=$\|39,6\|$ - in the case of an increase in the number of holes between discs (in rows) PLOT=2, and in the case of PLOT=1, Q=$\|16,8\|$, which can be considered a value that coincides with the evaluations of the power function (Q=$\|14,7\|$) of rice and triticale.

The results obtained from the machine test, the function of cross-section and momentary volumes in the form of dependencies (11) are sufficient for a general function of grinding intensity in grain motion to be formulated:

$$I_{DR}=\mathrm{k}\left(\left(1-\frac{Sc\cdot x}{V_g^p(\alpha_o)-V_{n+1}^m}\right)\rho_n^m(x)+\frac{Sc}{V_g^p(\alpha_o)-V_{n+1}^m}\int_x^{l_{max}}\rho_n(l)\,dl\right)\cdot\frac{N}{E};\frac{dm^3}{m\cdot W} \tag{16}$$

This function can form the basis for further optimisation or modernisation of the multi-disc and multi-hole grinding structure used for the grinding of e.g. triticale and rice, with high level of its compliance with experimental results.

4. Results analysis

With the stabilised motion of grinding components ((n,ω,v)=const), for the analysed scope of grain movement and with the use of functional models, it is possible to acquire knowledge of and design mutual relations within the multi-hole and multi-disc system of the grinder working unit: filling of the transport and grinding area, power, process target and mass efficiency as well as linear (circumferential) and rotational speeds of operating discs.

The systematised characteristics of idle running and load, based on specialist calculations and investigations into grinders, indicate that the filling of the quasi-cutting unit, and therefore efficient, power demand and energy consumption in the grain cutting process, depend on the values of operating speeds of both quasi-cutting and feeding. These, in turn, depend on motional and drive parameters of individual grinding units and the sum of momentary cross-sections, material volume in adjacent holes, making up a grinding unit. The grain motion characteristics, at various stages of disintegration and movement, depend on the common areas of the preceding and subsequent holes and their filling level with material both before and behind the cutting plane.

Applying a practical approach related to the structure and operation of food machines–assuming a design solution (as a logical conjunction of criteria and structural features of a quasi-cutting unit) within the conceptual space, providing an optimal solution from the point of view of the selected criteria including objective, minimum power, auto-adjustment and multi-level structure–it is possible to propose a new pro-developmental solution with regard to further analyses of the integrated grinding system in the field of permissible variability of structural features and processing parameters.

5. Conclusions

The methodology of calculations and examination of the characteristics of grain motion, for idle and loaded grinding, may lead to improvement and development of processing machines.

The selected characteristics of grain motion point to the need for reaching a compromise between the two basic functions: movement and grinding within the intra-hole working space. Proposed and partly verified models will facilitate selection of optimal structural features and multi-disc grinding process parameters. It is a useful and desired course, resulting ultimately in obtaining a nutritious/high energy product with a defined form, structure and repeatable dimensions.

The analysis of the current studies and structural basics of triticale, maize and rice grain grinders, as well as detailed mathematical descriptions of the grinding process in relation to the structure of disintegrating units confirm the possibility of development and experimental verification of mathematical models useful for optimisation (modernisation and advancement) of multi-disc grinding structures. Models and corresponding mathematical dependencies facilitate efficient designing and planning of multi-hole grinding systems utilisation.

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