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MODIFICATION OF GRINDERS OF BIOMATERIALS USED FOR ENERGY PURPOSES

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Abstract

Grinding of biological materials is an energy-consuming process. During grain decohesion, complex strain state occurs induced by compressing, twisting, bending, tearing, cracking, grinding or shearing. The work attempts to find structural solutions of the grinding and process control system enabling to increase rice grinding functionality: efficiency, energy-saving and regularity. The practical aim was to develop the methodology for innovative research on grain grinding which supports development of grinders.

Based on theoretical discussions and earlier scientific research, it can be concluded that it is possible to obtain optimal quality of material being ground and satisfactory functionality of the rice grain grinding process within a permissible range of values of the multi-disc grinder structural features. The exceeding of these values will result in the worsening of the process effectiveness and the quality of a grinding product. Finding relations between functionality, operation regularity, selected movement and energy related characteristics of the grinding process and structural features of the biomaterial grinding unit justifies the need for carrying out an analysis, studies and experiments with quasi-shearing in order to determine the indexes of the research object model variables.

***Key words**: structure; grinding; optimisation*

1. Introduction

The analysis of the transformations and states of operational efficiency of biomaterial grinders aims to solve the issue of the momentary conversion of the biological medium into a structural element subjected to the complex load state. This conversion is connected with a transfer of grinding loads and maintaining, or even increasing, its natural properties, e.g. energy value – as the basic objectives of grinding, e.g. environmental objectives of processing effected by machines [2,3,4].

The aim of the work is to analyse energy effectiveness, efficiency and grinding regularity of rice grains with the aim of optimising and developing the structure of multi-disc grinders. The practical aim was to develop the methodology for innovative research into grain grinding which facilitates the designing of grinders.

2. Research issue

The research issue was formulated in the form of a question: what structural conditions *(W_k)*, parameters and structural features of tools *(C_{KN})* in used and analysed grinders *(ZR_{BMZ})* and rice grain property variables *(W_{RR})* are necessary for optimal realisation of the grinding process *($PR_{optimum}$)*.

$$\{[W_k (C_{KN}) ? \cap W_{RR} ?] ZR_{BMZ}\} \Rightarrow PR_{optimum} . \quad (1)$$

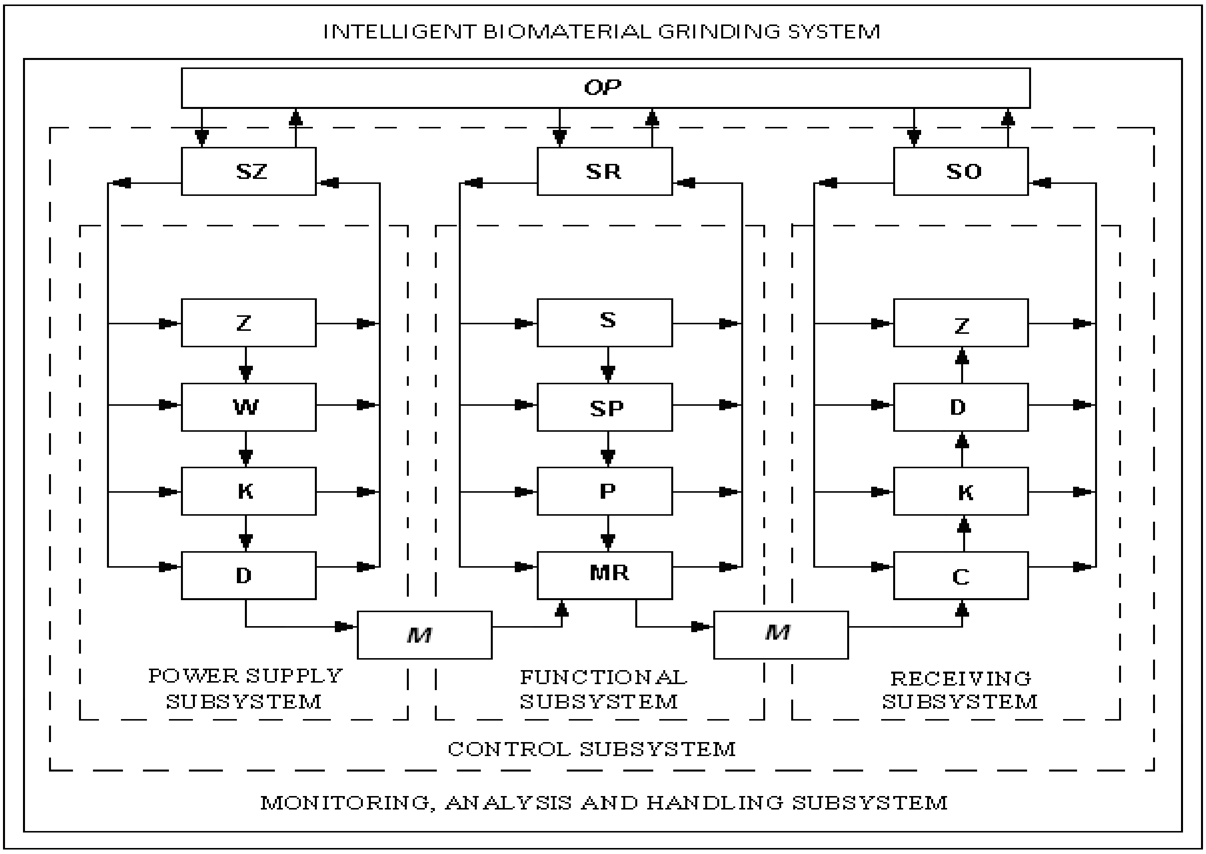
Structural conditions (W_k) are determined by structural features (C_k) of the multi-disc and multi-edge unit in terms of: geometrical form (Π_k), number of discs (l_t), number of movable blade edges (l_k), number of tool holes in discs (l_{otw}), number of hole rows (l_{rz}), hole diameters (d_{otw}), angles of edge blades or holes (β_{ij}) and other material and dynamics related features ($C_{k\text{-}m\text{-}d}$) of grinding elements.

As the solution estimators, the postulated states (SP_u) of the grinding process were taken: minimum power consumption (N_u), rational productivity (W_u), high energy effectiveness of the process (E_u) and product quality (Q_R).

The hypothesis was proposed that obtaining optimal quality (J_{proc}) of the grinding process is possible within a certain range of structural parameters of the multi-disc grinder and the exceeding of these parameters or changes of the form or dimensions results in the worsening of the product quality and process effectiveness.

$$For \mapsto \{[\ \rightarrow P, \rightarrow Q, \uparrow \eta, \uparrow e_R, \uparrow J_P\ ] \cap [f_{dz}(x_i), f_u(x_j)]\} \Leftrightarrow [\ (C_k^* \in \langle X_n, X_m \rangle \Rightarrow \uparrow J_{proc}) \cup (C_k^* \notin \langle X_n, X_m \rangle \Rightarrow \downarrow J_{proc})\ ], \quad (2)$$

where:
P – power,
Q – productivity,
η – efficiency,
e_r – process energy consumption,
J_p – product quality,
X_m,X_n – boundary values of structural parameters.



INTELLIGENT BIOMATERIAL GRINDING SYSTEM

Fig. 1: Intelligent biomaterial grinding system; OP – process handling, SZ – power supply control, SR – grinding control, SO – handling control**,** min: Z – tanks, W – selectors, K – conveyors, D – feeders, MR –grinding machines, P – gears, SP – couplings, S – motors; M – magnetic separators, C – cyclones

If the intelligent grinding system (figure 1) does not have postulated operating characteristics desired by the operator (e.g. it is characterised by low effectiveness of operation, insufficient product quality, adverse effect on the environment), the causes for this may be the following:

1. Respective system constituents; cause: deformed elements or erroneous relations between them,
2. Control system; cause: incorrect control effect,
3. Biomaterial grinding process; cause: incorrect concept of process realisation and incorrect control effect.

The expected functional status of an operational grinding system comprises the following process development models [5,6]:

1. Effectiveness of operation – data on product structure and operating system characteristics are available,
2. Product quality – data on product quality (e.g. grinding fineness and percentage content of the expected fraction) are available,
3. Mutual effects, lives, safety – data are available on the effects of system operation and product.

In search of desired solutions aimed at development of the rice grain grinder structure, an optimisation procedure should be conducted, e.g. analytical or enumerative (notional) methods, random search for solutions or genetic algorithms.

3. Model of the subject of research

Instantaneous values of angular velocities and torque allow determination of the following grinding process parameters:

- kinematic grinder gear ratio, (i_k),
- dynamic grinder gear ratio, (i_d),
- power at the gear entry equal to the power at the exit from the drive motor, (N_1),
- power at the exit from the gear equal to the power at the grinder shaft, (N_2),
- drive efficiency (η_p).

Finding the relation between functionality, operational regularity, selected movement and energy related characteristics of the grinding process (H_u) and structural features of the rice grinding unit (C_k) justifies the need for carrying out analyses, studies and experiments with quasi-shearing in order to determine the indexes of model variables. The following constructional criteria were adopted:

- optimal loads, (M_{op}, P_{op}),
- optimal material, (C_{km}),
- optimal stability, (C_k, Δ_e),
- optimal relations between related values, (E_R, δ_d, η_o, Q_s,Q_j).

Design process (innovation and development) should be guided in such a way so that the conditions of the grinder usefulness meet structural features [9]:

- maximisation of the function of regularity, efficiency, productivity, fineness for:

$$\left\{C_k^* \in \phi\right\}:\left\{\underset{c_k \in \phi}{\wedge} H_u(c_k) < H_u\left(c_k^*\right)\right\} \text{ dla: } H_u,: e_R \uparrow, W_u \uparrow, \eta \uparrow, \lambda \uparrow \quad , \tag{3}$$

- minimisation of power demand, energy consumption per unit, energy dispersion:

$$\left\{C_k^* \in \phi\right\}:\left\{\underset{c_k \in \phi}{\wedge} H_u(c_k) > H_u\left(c_k^*\right)\right\} \text{ dla: } H_u: N_u \downarrow, E_T \downarrow, M \downarrow, \omega \downarrow, v \downarrow, n \downarrow \quad , \tag{4}$$

where:
C_k^* - solution to the task,
Φ – permissible area of the structural features vector,
H_u – performance characteristics of the structural features vector.

Dynamic irregularities (fig. 2) of grinder operation can be described mathematically as per the following formalisation [9]:

- exponential:

$$M(t) = M_1 e^{jn\omega t} + M_2 e^{jn\omega t} + ... + M_n e^{jn\omega t} \quad , \tag{5}$$

- trigonometric:

$$M(t)=a_0+c_1 cos(n\omega t+\varphi_1)+ c_2 cos(n\omega t+\varphi_2)+....+ c_n cos(n\omega t+\varphi_n). \tag{6}$$

Diagrams of random variable cumulative distribution function $E(M, \omega)$;

- dynamic:

$$E_t(M) = P\,[\,M(t) < x] \quad \text{and} \quad E_{t+\Delta t}(M) = P\,[M(t+\Delta t) < x], \tag{7}$$

- kinematic:

$$E_t(\omega) = P\,[\,\omega(t) < \omega] \quad \text{and} \quad E_{t+\Delta t}(\omega) = P\,[\,\omega(t+\Delta t) < \omega]. \tag{8}$$

where:
M – torque at the grinder shaft,
ω – angular velocity of the grinder shaft.

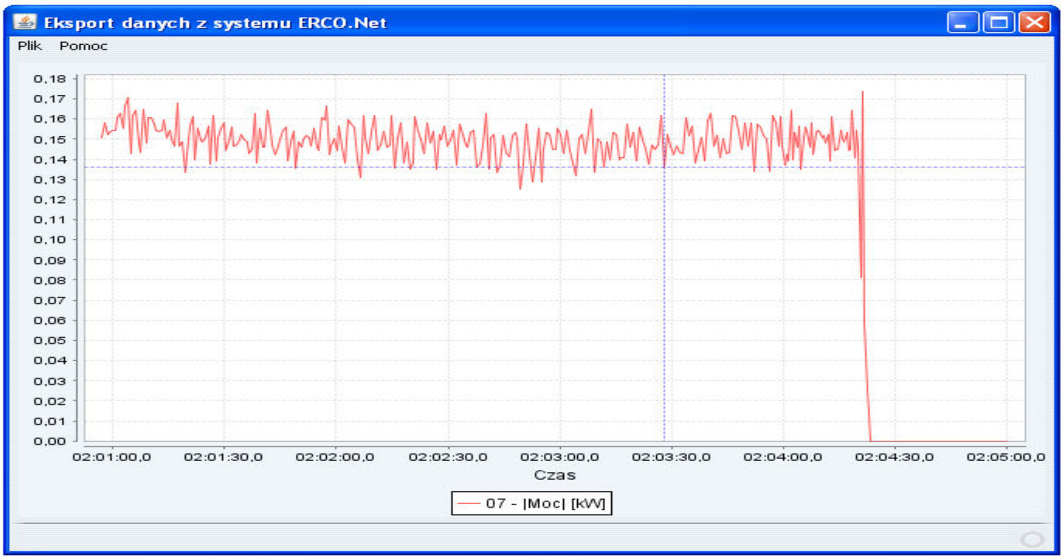


Fig. 2: Instantaneous power demand (irregularities) during grinding of rice grains using a multi-disc grinder RWT-5

Statistically presented grinding process is constant if obtained cumulative distribution functions are equal;

$$E_t(M,\omega) = E_{t+\Delta t}(M,\omega). \tag{9}$$

4. Model discussion

Expected structural features from the field of possible solutions to the design and structural task for the model of the subject of research are a function of many variables (maximised and minimised indexes) and therefore:

$$C_k = f(\eta\uparrow, W\uparrow, N_e\downarrow, E_T\downarrow, \omega\downarrow, M\downarrow, v\downarrow, n\downarrow), \tag{10}$$

where:
C_k – solution to the design and structural task.

The effectiveness model assumed is the dependence defining the increase in the grinding energy effectiveness

$$\Delta e_R = \frac{K_E}{E_R} = \frac{(\Delta)E_{pp}}{(\Delta)E_{R\lambda(F)}}, \tag{11}$$

where:
K_E - energy benefits, $Jg\cdot 1^{-1}$,
E_E - energy input, $Jg\cdot 1^{-1}$,
E_{pp} - processability energy, $J\cdot g^{-1}$,
$E_{R\lambda(F)}$ - grinding energy (phenomenon), e.g. for obtaining a product with desired fraction and postulated weight share expressed in percents, $J\cdot g^{-1}$.

The grinding process effectiveness can be defined by determining energetic, economic and ecological effectiveness.
Power demand required to achieve efficient and expected biomaterial grinding can be determined by using one of the known grinding theories. According to Rittinger, grinding energy equals:

$$E_R = K_R \frac{6}{d\rho}\left(1 - \frac{1}{n_i}\right), \tag{12}$$

where:
K_R – energy required to generate a surface increase unit as per Rittinger, $Jg \cdot m^{-2}$,
ρ – material density $Mg \cdot m^{-3}$.

The efficiency of the grinding process is determined by specifying the following: bioenergy material acquisition efficiency, processing (production) efficiency, use (utilisation) efficiency [1]. A calculation model supplemented with detailed relation for effectiveness and grinding regularity. To assess energy specific consumption for multi-edge grinding of rice grains, the following mathematical formula [8]:

$$E_R = \frac{P_R v_R t}{\eta_S \eta_P}, \tag{13}$$

where:
E_R- unit consumption of energy for machine grinding, J/g,
P_R- grinding force load, $N \cdot g^{-1}$,
v_R – grinding speed, $m \cdot s^{-1}$,
t – cycle duration, s,
η_S – motor efficiency, -,
η_P – transmission efficiency, -.

That dependence does not take into account specificity of grinding for energy purposes; therefore, a general model of energy effectiveness of the machine-based multi-disc grinding process has been formulated as follows:

$$e_R = \frac{\Delta E_{bio}}{E_R} = \frac{(\eta_{bio} - \eta_z) \cdot E_{gross} \eta_S \cdot \eta_P}{\left(k_j v_R + \sigma_{\max} F_R + \varepsilon F_R v_R^2\right) v_R t M_k}, \tag{14}$$

where:
ΔE_{bio} – index of an increase of energy benefits (for further tasks) resulting from the grinding process, kJ/g, (0.40-0.48)E_{gross},
η_{bio} – efficiency of ground product incineration, (0.50-0.98),
η_z – efficiency of whole rice grain incineration, (0-0.49),
E_{gross} – gross energy of grains, $kJ \cdot g^{-1}$, (rice E_{gross}= 14.1 $kJ \cdot g^{-1}$),
k_j – resistance coefficient for lost motion, Nsm^{-1},
σ_{max} – stresses related to permanent deformation, Nm^{-2},
ε – dynamic resistance coefficient, Ns^2m^{-4},
M_k – ratio of the analyzed mass to 1 g,
F_R, F_R' – grinding section, m^2.

A model described with the above dependence is very useful in evaluating the incineration process, energy effectiveness of operation, efficiency and functionality. However, it is not very useful in analysing instantaneous irregularity of grinder run and operation. The basic problem is that the variability of mass characteristics of biomaterials, functional working, driving and process units has to be taken into account each time. For the purpose of describing, modelling and evaluating the functionality of work of the analysed grinders it is more convenient to use special motion models and in particular – dynamic irregularity dependence. For the purpose of detailed analysis of dynamic irregularity, modification of moment relation was used and the average value of torque transformed into the following form:

$$\delta_d = \frac{M_{c\max} - M_{c\min}}{M_{c\acute{s}r}} = \frac{2\pi\left[p_c \Delta l_{\max} r\cos\tau(1+\mu tg\tau) - p_c \Delta l_{\min} r\cos\tau(1+\mu tg\tau)\right]}{z\int_{\varphi_P}^{\varphi_K} M_C(\Psi)d\Psi} = \tag{15}$$

$$= \frac{A(\Delta l_{\max} - \Delta l_{\min})}{M_{Csr}},$$

When invariability of unit grinding resistance and friction conditions are taken into account, the dependence takes a convenient form that may be used for measuring procedure. The degree of dynamic irregularity, measured for instantaneous settings of knife unit, is determined on the basis of measurement of instantaneous cutting length Δl_i – with determination of extreme values; and instantaneous torque M_i and determination of the average value. Under test conditions, the value of A constant is also determined for design of the multi-edge system design, rice grains and parameters of the disintegration process defined in the research programme.

5. Research results

Research has been conducted on the basis of the research plan and programme, (Fig.1, Fig.3).

EXPERIMENT PROGRAMME		
Properties of ground material [7]:	Working parameters of grinder	Technological parameters
1. humidity 2. bulk density 3. angle of repose 4. viscosity 5. structure of biological material 6. strength values	1. number of holes in discs 2. number of hole rows in first and subsequent discs 3. gap between discs 4. hole diameters 5. diameters of hole distribution on disc 6. angle of cutting edges 7. number of discs	1. angular speed 2. direction of disc rotation 3. rotational speed of feeder screw
MULTI-DISC GRINDING		
Result relations:		

Mass productivity	Calorimetric indexes	Fineness	Power demand

Fig. 3. Experiment programme

The simulation tests were conducted to determine sections and loads. Computer-based TEST-4 procedure was applied (Fig.4).

The machine-based tests were conducted using a multi-disc multi-hole grinder RWT-5:KZ owned by Engineering Systems and Environmental Protection Unit of the University of Technology and Life Sciences in Bydgoszcz. Rice grains with stabilized humidity parameter were used as the feed material. Figure 5 shows comparison between experimental and calculation-based results, figure 6 shows the influence of rice grain humidity on energy demand of 5-disc RWT-5KZ grinder, and figure 7 – influence of grain batch feed on demand of the analysed grinder. Fig. 8 shows instantaneous values of torque (M_{01}-M_{05}) for five discs of the grinding unit.

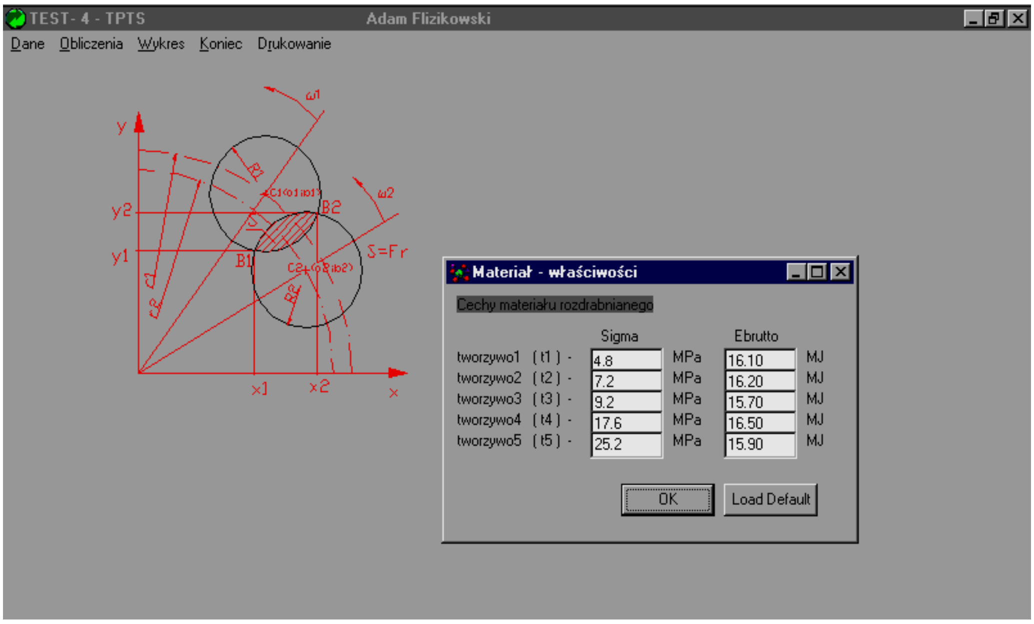


Fig. 4. Results of grinding load simulation

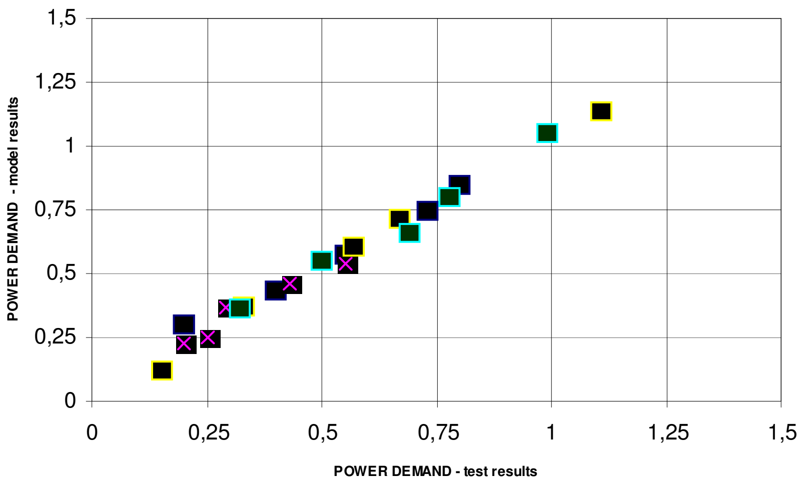


Fig. 5. Comparison between test results and mathematical model results P=f(Z,W)

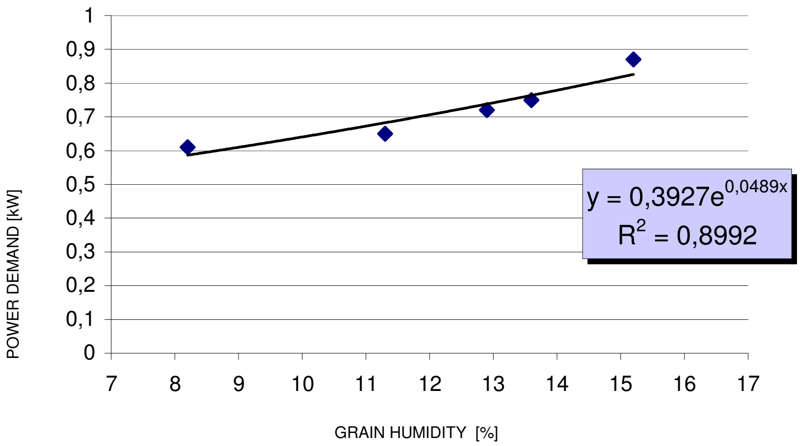


Fig. 6. Influence of rice grain humidity on power demand of the RWT-5:KZ multi-hole grinder

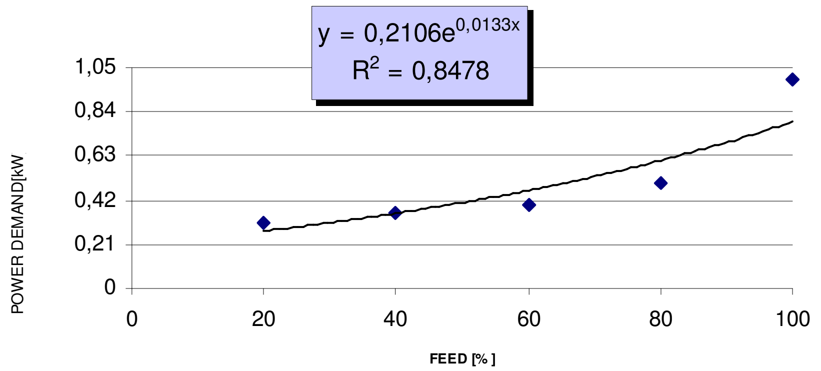


Fig. 7. Influence of the rice grain feed on power demand of the RWT-5:KZ multi-hole grinder, digitally controlled loose material feeder: Hydrapres DSK07/10I

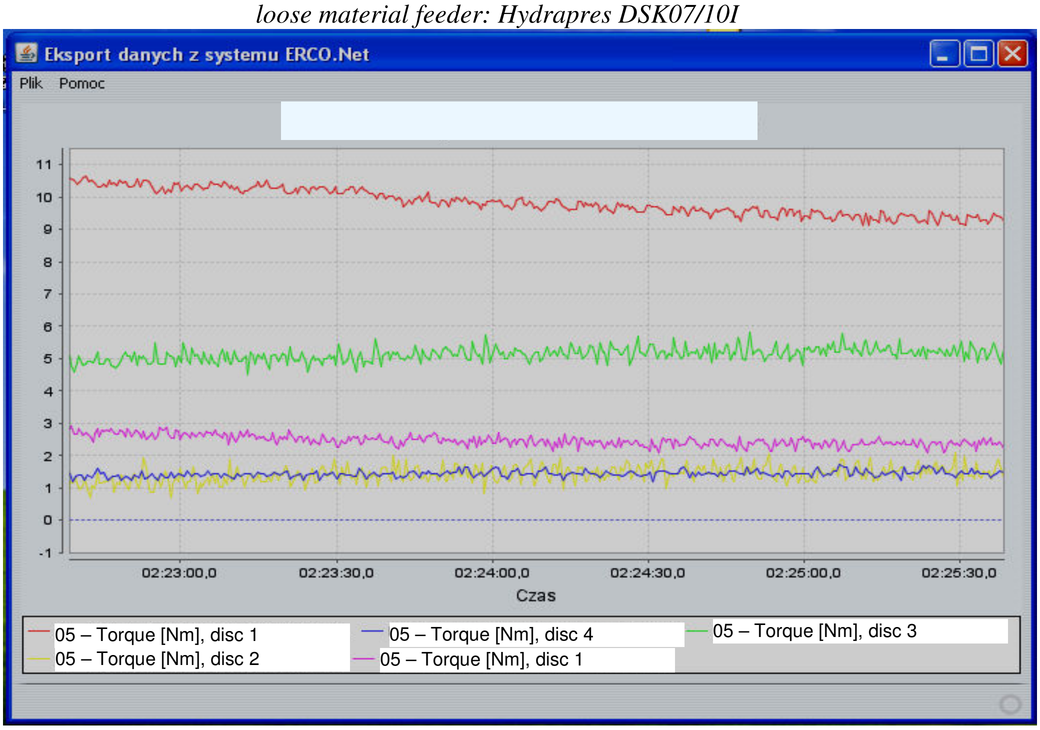


Fig. 8. Instantaneous values (irregularities) of power demand, all disc

When looking for design (structural) features of the working unit that fulfil solution of the task and additionally condition of maximum incineration heat Q_s, structural features of the working unit of RWT-5;KZ multi-hole, multi-edge grinder (table 1);

$$[\ (C_k^* \in \langle X_n, X_m \rangle \Rightarrow \uparrow J_{proc}) \cup (C_k^* \notin \langle X_n, X_m \rangle \Rightarrow \downarrow J_{proc})\ ] \qquad (16)$$

Tab. 1.Changes of incineration energy of ground size fractions of rice, kJ/g,

Sample	Fraction	Wire weight	Sample weight	W^r_{ex} [%]	A^a [%]	H^a [%]	Q_s [kj/kg]	*Qj* [kJ/kg]
1	0.2 ÷ 0	0.006	1.014	13.5	4.6	4.427027	16740	15443.844
2		0.007	1.022	13.5	4.6	4.427027	16650	15353.844
3		0.005	1.013	13.5	4.6	4.427027	16630	15333.844
4		0.005	1.018	13.5	4.6	4.427027	16690	15393.844
5	0.45÷0.2	0.006	1.013	13.5	4.6	4.427027	16340	15043.844
6		0.005	1.016	13.5	4.6	4.427027	16070	14773.844
7		0.006	1.009	13.5	4.6	4.427027	16410	15113.844

8		0.005	1.01	13.5	4.6	4.427027	16420	15123.844
9	0.8÷0.45	0.006	1.008	13.5	4.6	4.427027	15570	14273.844
10		0.006	1.01	13.5	4.6	4.427027	15700	14403.844
11		0.005	1.008	13.5	4.6	4.427027	15650	14353.844
12		0.005	1.01	13.5	4.6	4.427027	15770	14473.844
13	1÷0.8	0.005	1.013	13.5	4.6	4.427027	16030	14733.844
14		0.005	1.008	13.5	4.6	4.427027	15930	14633.844
15		0.005	1.015	13.5	4.6	4.427027	15580	14283.844
16		0.005	1.011	13.5	4.6	4.427027	16030	14733.844
17	1.4÷1	0.006	1.019	13.5	4.6	4.427027	15800	14503.844
18		0.005	1.01	13.5	4.6	4.427027	15380	14083.844
19		0.007	1.007	13.5	4.6	4.427027	15520	14223.844
20		0.006	1.008	13.5	4.6	4.427027	15490	14193.844

The ground rice has been subjected to calorimetric incineration tests taking into account size fractions and fineness. The results obtained are shown in table 1.

6. Summary

In the light of results of mathematical and experimental study, formalization of irregularities, with rice grain grinding used as an example, for selected parameters of determined functions and random function shows that the assumptions made are correct. The analysis should, however, include detailed verification of assumptions related to ergodicity and constancy of characteristics of torque, angular speed and power at shaft (shafts) of the grinder.

For the uniform operation of multi-edge grinders it is necessary, within the given area of assumptions, to propose modified models of irregularity of machine runs, taking into consideration: unit shearing resistance p_c, friction μ and other conditions of quasi-shearing of heterogeneous materials, for determination of specific value describing the material and selected conditions of the grinding process.

On the basis of the presented model and research programme, structural features of the unit that evenly grinds rice grain has been selected, with the operational irregularity within ($\delta d \leq 10$) %.

Energy effectiveness, regularity, energy consumption, rice grinding efficiency, working resistance for the gain in specific surface area, increases in incineration energy and temperature, power consumption and stream of the grinding process productivity, depend on motion of elements and therefore on properties of ground materials and design of the machine used.

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Reference

[1] Detyna, J., *Analysis of nonequilibrium stases in the sieje separation process,* Maintenance and Reliability 1(49)2011: 78-85.

[2] Flizikowski, J., *Konstrukcja rozdrabniaczy żywności,* Wydawnictwo Uczelniane Akademii Techniczno – Rolniczej w Bydgoszczy, Bydgoszcz 2005.

[3] Flizikowski, J., Bieliński, K., Bieliński, M., *Podwyższenie energetycznej efektywności wielotarczowego rozdrabniania nasion zbóż na paszę,* Wydawnictwo ATR-OPO, Bydgoszcz 1994.

[4] Flizikowski, J., Bieliński, M., *Rozdrabniacz wielotarczowy zwłaszcza do materiałów ziarnistych*, Patent RP.

[5] Mroziński, A., *Modelling of waste-paper stock treatment process in disc refiners*, Journal of POLISH CIMAC nr 3/2010, Vol. 5, str. 113-119.

[6] Mroziński, A., *Podstawy rozwoju przetwarzania mas makulaturowych w młynach*, Ekologia i Technika, Vol. 101, nr 4 (2009), str. 151-158.
[7] Razavi, S.M.A., Farahmandrar, R., *Effect of hulling and milling on the phisical properties of rice grains,* International Agrophisics, 2008, 22, 353-359.
[8] Tomporowski, A., *Testing thy power of multi - disc shrebing grains of rice*, Ekologia i Technika nr 3, s. 161-164.
[9] Tomporowski, A., *Assumptions to the formalization of the courses of grinding irregularities by means of the random function,*. Ekologia i Technika nr 6 (2009), s. 317-320.