Control and monitoring of multi-disc comminution process

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Abstract. The article deals with the issues of intelligent, based on genetic algorithms, systems for grinding of grainy biomass to be used for further energy production processes. The aim of the study is to develop the basis for processing, active monitoring and subsequently, adaptive control of the process functional characteristics on the basis of solutions provided by artificial intelligence and identification of input variables of mathematical models and indexes, their mutual relations as well as their impact on the output variables such as: degree of fineness, production yield, power demand and unit energy consumption as well as CO_2 emissions. A research methodology for practical control of the grinding potentials to improve the parameters of the multi disc grinding process parameters including: energy and power consumption, the product granulometry and the process efficiency improvement; CO_2 emission index being a determinant of environmental efficiency has been developed. Parameters providing the grinding process with best possible conditions in terms of energy efficiency and emissivity, depending on the kind of the feed material, have been determined

1. Introduction

Diversity of materials used in grinding and their variable properties enable to create new and more complex structures of grinding systems to ensure the lowest possible energy consumption and the highest efficiency [1–3]. Thus, optimization of the grinding process involves determining parameters that would provide a given material and a grinder with high energy and environmental and qualitative efficiency to be measured by the assumed degree of fineness [4–6]. Determination of values for optimal setpoints in result of tests performed for different variants, needs much time and large databases. This raised the need to implement regulation and control systems based on the idea of active monitoring and genetic algorithms into the process of grinding. So far research on multi disc grinding, performed with the use of genetic algorithms, has been focused on achievement of the highest possible energy efficiency [7–9].

Intelligent management and control systems based on evolution methods, that is, methods of genetic algorithms, have been known since the 80s of the 20th century. In relation to grinding, these methods have been analyzed for the last 15 years which has led to creation of a biomass grinding line consisting of fully automated stages. Application of the so called artificial intelligence and machine learning makes the control modules automatically optimize the grinding process for a given material, in compliance with the requirements regarding the product granulometry and maintaining the possible lowest energy consumption and emissivity of e.g. CO_2 [10], [11].

Development of grinding systems using intelligent control and monitoring systems, and subsequently, selection of optimal parameters, structural features and grinding methods can take place only when the following criteria are fulfilled: the structure quality is maintained, energy consumption is minimized, the properties of the product are improved, the assumed granulometric distribution of the product particles is achieved, the assumed rotational range speed of discs is provided [12–15].

In the light of the above, the goal of this study includes: (i) determination of the basis for processing, active monitoring and, in consequence, adaptive control of functional characteristics, based on artificial intelligence solutions, (ii) identification of mathematical model input variables and indexes and their mutual relations as well as the impact on the output variables: degree of fineness, production yield, power demand, unit energy consumption and CO_2 emission.

2. Materials and methods

2.1. Algorithm for five- disc RWT-KZ5 grinder

Genetic algorithm seeking optimal setpoints of the grinder parameters was created for a five-disc grinder RWT-KZ5 which is in the research laboratory for grinding (WIM, UTP).

D domain was accepted for this grinder:

$$D =< 20;100 > \mathrm{rad} \cdot \mathrm{s}^{-1} \text{ and } < 50;100 > \%$$

The minimal and maximal values of discs angular speeds result from structural conditions of the grinder propulsion system and load application possibilities of the drive engine. The maximal value of the feed material dosing depends on the possibility of load application to the stepper motor controlling the feed material supply, whereas the minimal value was accepted on the basis of the observation that below this feed material supply value the grinder is used with throughput smaller than 50% of its maximal capacity.

Code chain of a genetic algorithm for a five-disc grinder consists of six genes encoded in a binary system. Genes of disc angular velocities were encoded by means of 6 bites, that is, velocity range from 20 rad·s^{-1} to 100 rad·s^{-1} was divided into 64 parts (so that they could be recorded in a binary system), which in practice means that changes of angular velocities occur every 1.25 rad·s^{-1}, after being rounded to integers, every 1 rad·s^{-1}, that is app. 10 rev·min^{-1}. Setpoints of the feed material supply efficiency of the range from 50% to 100% were encoded on 5 bites (division into 32 intervals in order to enable encoding in a binary system), which means that efficiency of feed material dosing is graded every 1.5%.

It was established that the population of the initial generation for this algorithm would be k=10. The best code sequences b=4 will be selected from the ranking list 10 best generations. Each new generation will consist of 2b=8 code sequences (Figure 1.). The number of i iterations is determined by the user in the control panel; for the research purpose, i=5 were assigned be default.

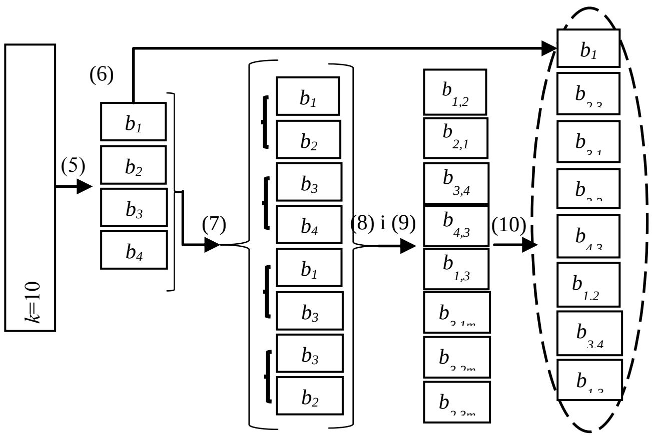

Figure 1. Scheme of creation of a new generation of code sequences

2.2. Grinding process assessment criteria

The research included determination of grinding process efficiency indicators, such as [5]:

- **production yield Q_r** ($g \cdot s^{-1}$)**,** which in observation time Δt of product weight changes Δm can be calculated basing on the formula [5]:

$$Q_r = \frac{\Delta m}{\Delta t}$$

- **specific energy consumption E_j** ($j \cdot g^{-1}$), expressed as [5]:

$$E_j = \frac{N_{cPR}}{Q_r}$$

- **80% grinding degree, –,** described as [5]:

$$i_{80} = \frac{D_{80}}{d_{80}}$$

where:
D_{80} – dimension of the sieve hole, through which 80% of the feed material passes,
d_{80} – dimension of the sieve hole, through which 80% of the grinding product passes.

- **CO_2 emission index -** can be identified as:

$$W_{CO_2} = \frac{m_w \cdot \sum_{i=1}^{n} (m^b_{iCO_2} \cdot E^b_{iw} \cdot Q_i) - Z_E \cdot m^w_{CO_2}}{Z_E}$$

where:
m_w – bulk expenditure, g,
$m^b_{iCO_2}$ – unit index of CO_2 for the i-th biomass fraction, $kg \cdot GJ^{-1}$,
E^b_{iw} – calorific value of i-th biomass fraction, $kJ \cdot kg^{-1}$
Q_i – share of i-th dimensional fraction, %,
Z_E – energy demand, kJ,
$m^w_{CO_2}$ – unit index of emission for coal , $kg \cdot GJ^{-1}$.

The above characteristics provide the basis for an analysis, evaluation and intelligent development of the structure and the milling process, according to the new concept of a multi-disc mill.

2.3. Research stand

The research stand for monitoring of functional characteristics of the milling process consists of the following modules: machine module (mill RWT-KZ_5), control module (application MŁYN 2018, subsystems for control, application AG_2018, sensors), logistic module (feed dosing system), power supply (electric wires, system of motors). A view of the stand is presented in Figure 2.

The major function of the control module is to control the five-disc mill through adaptive change of the disc angular speeds and the rate of feed material supply. Additionally, it is supposed to register and archive the values of functional parameters such as: power consumption, efficiency, degree of product particle fineness.

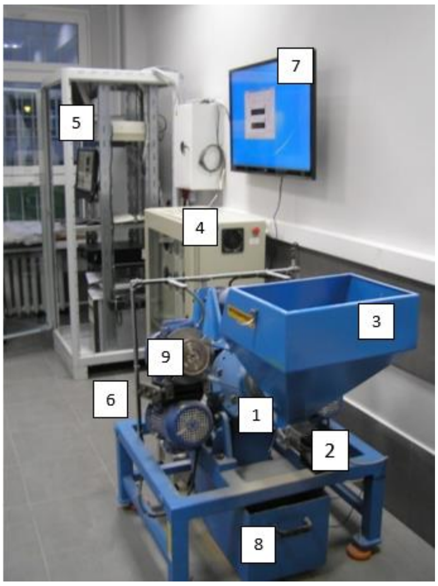

Figure 2. Research stand: 1- five-disc mill RWT_5KZ, 2- feeding screw, 3-hopper, 4- control box, 5- control unit with PC and modules for data processing and archiving, 6- system for identification and measurement of grinding product particle size, 7- results display monitor, 8- product basket, 9- propulsion system with belt -tooth transmissions

2.4. Conditions of the experiment
Rice grains of medium moisture 13.6% and substitute diameter D_{80} = 2.23 mm were subject to grinding.

Table 1. Input values accepted for determination of CO_2 emission index

	Size of fraction (μm)	0-630	630-1250	1250-2000	>2000
Rice	E^b_{iw} (kJ·kg^{-1})	14276	14145	13990	13872
	$m^b_{iCO_2}$ (kg·GJ^{-1})	116.8	95.2	194.0	293.7

To determine the values of CO_2 emission index, the value of unit emission index CO_2 $m^b_{iCO_2}$ and calorific value E^b_{iw} have been accepted for the processed grains which is presented in Table 1. Unit index of CO_2 emission for coal was accepted to be 95.48 kg·GJ^{-1} [16].

During grinding, such parameters as: power demand on each disc and the product weight in the basket, were recorded for the grinding product time changes, for each disc speed configuration (Table 2).

Table 2. Configurations of disc angular speed

No of config.	V_p (kg·h^{-1})	ω_1 (rad·s^{-1})	ω_2 (rad·s^{-1})	ω_3 (rad·s^{-1})	ω_4 (rad·s^{-1})	ω_5 (rad·s^{-1})
1	102	60	70	80	90	100
2		50	60	70	80	90
3		40	50	60	70	80
4		30	40	50	60	70

3. Results

3.1. Results of parameters monitoring
Figure 3 presents the results of energy consumption observed for each disc in dependence on the disc speed for rice grinding. Each point of the disc represents one configuration of the disc speed.

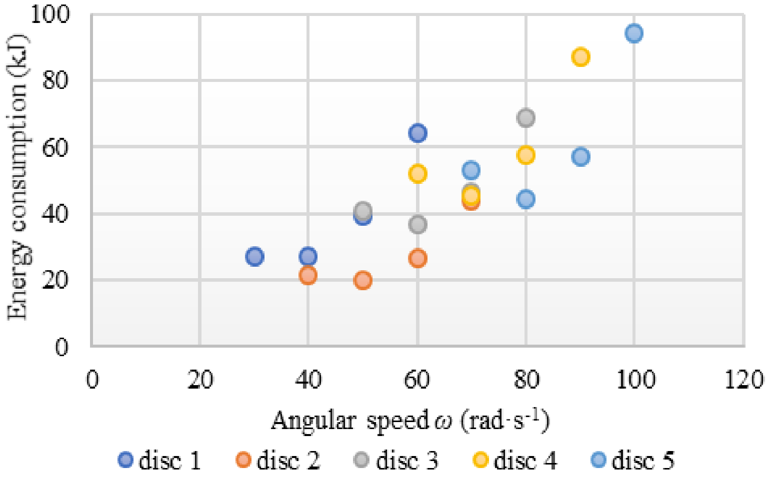

Figure 3. Energy consumption for each disc in five disc mill in dependence on disc speed – rice grinding; each point of disc represents one configuration

Basing on the results shown in Figure 3 it can be said, that the highest energy consumption occurred for the disc with the highest speed – the first disc. The results allow to say that as the angular velocity of the discs increases, the energy consumption during grinding increases.

Table 3 presents the results of monitoring of specific energy consumption E_j, production yield Q_r and grinding degree i_{80} for each disc speed configuration. Considering rice grinding, the highest specific energy consumption E_j (486424 J·kg^{-1}) was observed for the second configuration of disc speed, the lowest for the fourth configuration (303850 J·kg^{-1}). The highest grinding degree i_{80} for this case was obtained for the first configuration (1.41), the lowest for the fourth configuration (1.15). Production yield Q_r for rice grinding was highest for the first disc speed configuration (14.20 g·s^{-1}), the lowest for the fourth configuration (12.55 g·s^{-1}).

Table 3. Results of monitoring the specific energy consumption, real efficiency and grinding degree for each disc speed configuration

Grains	No of config.	E_j (J·kg^{-1})	i_{80} –	Q_r (g·s^{-1})
Rice	1	358053	1.41	14.20
	2	486424	1.28	13.71
	3	467425	1.18	13.80
	4	303850	1.15	12.55

It was observed that while the disc angular speed decreases, the specific energy consumption decreases too. Similar effect was observed for other mills ex. impact mills, crushers [17–19]. Different results were obtained for the developed by the authors roller mill with inter roller plate [5]. For that roller mill the specific energy consumption decreases, while the roller speed increases, which is caused by higher dynamics of efficiency growth than energy demand increase. Similarly to specific energy consumption, while the disc angular speed decreases, the grinding degree i_{80} decreases too, which is consistent with previously conducted research for disc mills published for example in [19].

3.2. *Experiment with genetic algorithm*

In Table 4 show values of grinding parameters (angular speed of discs, chargé hopper output) of rice grains obtained for particular generations of genetic algorithms. Figures 14-21 shows the results of product yield $Q_{(0,9)}$, power consumed by the mill, quality of the product defined by the fraction percentage content, CO_2 emission index for rice grains obtained using genetic algorithm for the values of angular speeds and the feeder capacity presented in Table 4.

Table 4. Angular speeds of discs ant the feeder capacity for a given GA code sequence during rice milling

Number of GA generation	ω_1 (rad·s^{-1})	ω$_2$ (rad·s^{-1})	ω_3 (rad·s^{-1})	ω_4 (rad·s^{-1})	ω_5 (rad·s^{-1})	V_p (%)
1	-39	-100	-79	66	-87	63
2	-86	-54	45	36	42	66
3	-128	-48	-98	-91	-87	77
4	69	-48	95	-48	-42	56
5	72	54	-98	-72	124	90
6	-83	74	48	-124	-121	58
7	-83	-38	-128	-54	-90	97
8	62	-120	-60	45	-79	65
9	52	54	64	106	79	68
10	-62	87	-89	-94	85	84
11	62	-120	-60	45	-79	65
12	-62	87	-89	-94	62	84
13	-83	127	48	-100	-121	58
14	52	107	64	106	85	68
15	-83	74	48	-124	73	68
16	52	54	64	106	-116	84
17	62	-120	-60	45	-79	58
18	-83	127	35	-124	-76	65
19	52	107	64	106	85	68
20	-62	87	-92	-94	85	84
21	-49	87	-89	-94	85	84
22	-116	107	64	106	82	68
23	-93	91	-89	-106	85	84
24	-49	-123	-60	45	-79	65
25	-83	127	48	-100	-121	58
26	-116	107	57	57	82	68
27	-110	54	64	106	82	68
28	-89	127	48	-100	-121	58
29	62	-120	-60	-121	-79	65
30	-49	-123	-70	45	-79	65
31	-49	87	73	-94	-87	84
32	-128	127	48	-51	-121	58
33	-49	87	-89	-94	-87	58
34	-89	74	35	-100	73	84

On the basis of the obtained results it is possible to say that during rice grain grinding optimal values of the process indexes: product yield $Q_{(0,9)}$ = 8.86%, product quality defined by the fraction percentage share $Q_{0\text{-}630}$=10%, $Q_{630\text{-}1250}$=16%, $Q_{1250\text{-}2000}$=28%, $Q_{>2000}$=38%, power consumption P=2,15 kW, CO_2 emission index 84.3 g·kJ^{-1} were obtained for angular speeds of the grinder discs equal to: ω_1=62 rad·s^{-1}, ω_2=-120 rad·s^{-1}, ω_3=-60 rad·s^{-1}, ω_4=45 rad·s^{-1}, ω_5=-79 rad·s^{-1} and for the charge hopper at the level of 65%.

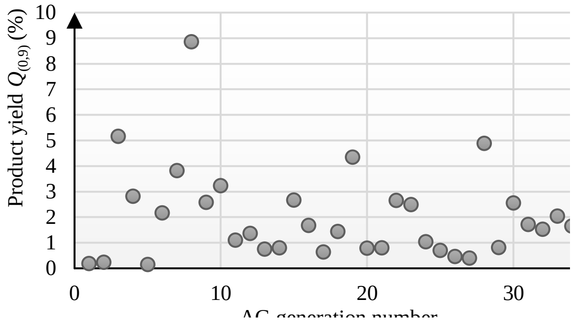

Figure 4. Results of research on optimization of grinding parameters by means of genetic algorithms – product yield

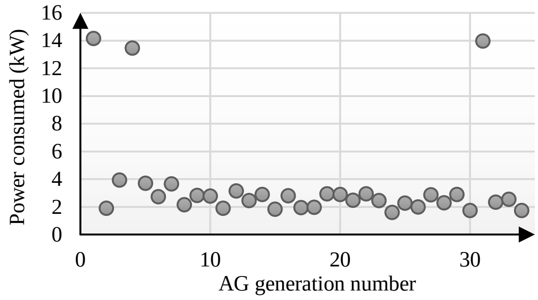

Figure 5. Research results of research on optimization of parameters of grinding by means of genetic algorithms – power consumed

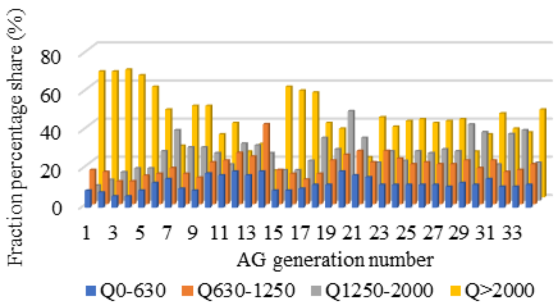

Figure 6. Results of research on optimization of grinding parameters by means of genetic algorithms – the fraction percentage share

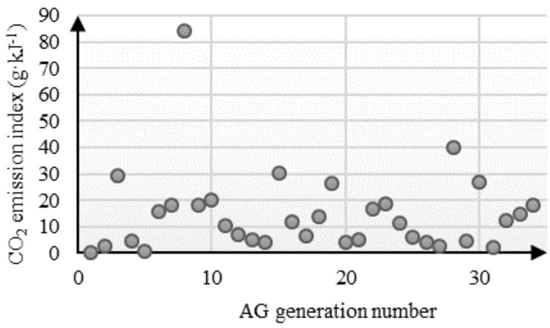

Figure 7. Results of research on optimization of the parameters of grinding by means of genetic algorithms – CO_2 emission index.

4. Summary and conclusion

The aim of this work has been achieved through development of the grinding process control system and analysis of rice and corn multi-disc grinding process with the use the original monitoring system and an experiment with genetic algorithms.

On the bases of the conducted research it was found that:

1. as the angular speed of the discs increases, the energy consumption during grinding increases,
2. while the disc angular speed decreases, the specific energy consumption decreases too,
3. while the disc angular speed decreases, the grinding degree i_{80} decreases too,

Using genetic algorithms, we may provide the auto-monitoring process with the following technical conditions: charge feeding intensity (with specified parameters: mean size d_{80}, humidity, angular speeds of grinding discs (ω_1-ω_5)), such that efficiency indicators reach the best values from the acceptable range

Developed mathematical apparatus, methods of analysis and synthesis of regulation of structures working in the feedback loop, algorithms of modelling and identification, theory of stability, theory of optimisation — all the subjects constitute the core of the proposed solutions.

Auto-monitors by definition serve as partners for operators who control processes and engineers responsible for maintenance. Higher autonomy of the cognitively active monitoring means lower necessity of human intervention which will be translated into higher safety (currently, human is the most uncertain factor) and efficiency of the processing.

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