New model for ecological assessment of comminution process in energy biomass processing chain

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Abstract. Acquiring energy contained in the biomass structure requires its prior appropriate preparation. These treatments require some energy inputs, which significantly affects the reduction of the energy and environmental balance in the entire life cycle of energy biomass processing chain. In connection with the above, the aim of the work was to develop a methodology for ecological assessment of biomass grinding in the processing chain for energy purposes. The research problem was formulated as follows: is it possible to create an assessment model that takes into account the environmental inputs and benefits of the grinding process of biomass intended for further energy use (combustion); how the control variables of the grinding machine affect the ecological evaluation of the process. In response to the research problem, the original index of ecological assessment of the biomass grinding process was developed. The model was verified by assessing the process of rice and maize grinding on a real object - a five-disc mill, for various settings of grinding discs speed. It was found that the developed ecological assessment model allows comparison of grinding processes and indication of the process with a more favorable CO_2 emission balance and its values depend on the control parameters of the mill.

1 Introduction

Grinding processes are one of the most commonly used preparatory processes for energy carriers (fossil and alternative) intended for combustion and co-combustion [1,2]. Grained biomass size reduction is predominatingly carried out on cylindrical mills, drum mills, ball mills, hammer mills and disc mills [3,4]. The best results in terms of the quality of the grinding product, energy consumption and efficiency are obtained for hammer and disc mills [1,3]. The main goals of grinding of granular biomass, as well as other energy materials (eg coal, wood) include: reduction of dimensions, release of substance contained in the material structure and increase of specific surface area of material, so that the energy contained in its structure could be released faster [5–8]. In order to maximize the potential of ground raw materials, energy consumption during grinding (processing) should be as

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low as possible [9]. Unfortunately, currently used mills and grinders continue to be characterized by high energy consumption and low efficiency [5,10]. It becomes a contribution to undertaking research, creating structural and technological solutions aimed at improving the energy and environmental efficiency of grinding systems. The key element is the implementation of eco-innovative systems, assessed starting of the design stage with use, for example, multicriteria analysis [11,12]. Criteria for selection of grinding technology and assessment of its operation should clearly indicate solutions that meet the assumptions of sustainable development [13,14].

Not many published papers have contained issues connected with the comprehensive (energy and environmental) assessment of grinding systems. In many works, specific energy consumption and fragmentation degree have been indicated as two basic criteria for the assessment of this process [15–18].

A multitude of issues and phenomena occurring during the grinding of biological materials, including biomass grains intended for the energy industry, requires taking into account a greater number of criteria adapted to the specificity of the company, the system, the mill design and material properties (its structure, chemical composition, humidity). Identification of variables and parameters influencing the final effect of grinding (product quality, energy consumption and process efficiency) enables determination of favorable conditions in which the obtained results are the best [3,10,19].

In connection with the above, the aim of the work was to develop a methodology for ecological assessment of biomass grinding in the processing chain for energy purposes. The research problem was formulated as follows: is it possible to create an assessment model that takes into account the environmental inputs and benefits of the grinding process of biomass intended for further energy use (combustion); how the control variables of the grinding machine affect the ecological evaluation of the process?

2 Materials and methods

2.1 Model of a sustainable CO_2 emission index

The emission of CO_2 equivalent in the grinding process is closely related to its energy consumption. Considering a system for which the aim is to improve the environmental impact of the process, product, machine (eg. by eliminating CO_2), while maintaining other objectives: increasing efficiency and obtaining a product with the desired quality as well as energy efficiency can be identified integrated energy purpose of product (combustion) sustainable CO_2 emission index expressed as :

$$W_{ZCO_2} = \frac{\Delta B_{CO_2}}{N_{CO_2}}$$

(1)

where:
ΔB_{CO_2} – environmental benefits – change in CO_2 emissions,
N_{CO_2} – environmental costs of grinding – energy consumption.

Environmental benefits were described as CO_2 emissions from the burnt ground energy biomass, because biomass is a renewable fuel, which during the growth phase absorbs the amount of carbon dioxide equal to emissions from its energy use [20]. Additionally, in industrial emission monitoring systems, CO_2 emission indexes from biomass are treated as zero [21]. These benefits were reduced by the equivalent CO_2 emissions related to energy consumption in the grinding process in accordance with the dependence:

$$\Delta B_{CO_2} = X_{BCO_2} - X_{RCO_2} \tag{2}$$

where:

X_{BCO_2} – CO_2 emissions from the energy use (combustion) of ground biomass, $kgCO_{2eq}$,

X_{RCO_2} – the amount of CO_2 emissions associated with the use of electricity in the grinding process, $kgCO_{2eq}$.

Emissions from the combustion of ground biomass X_{BCO_2} are expressed as the sum of emissions from the combustion of biomass divided into size classes, according to the dependence:

$$X_{BCO_2} = m_B \cdot \sum_{i=1}^{n} \left(J_{AiCO2} \cdot W_{iB} \cdot q_i \right) \tag{3}$$

where:

m_B – mass of ground biomass, kg,

J_{AiCO2} – unit CO_2 emission for the i-th size class of biomass, $kg \cdot kWh^{-1}$,

W_{iB} – calorific value of the i-th size class of biomass, $kWh \cdot kg^{-1}$,

q_i – mass share of the i-th size class of biomass.

The emissions related to the consumption of electricity during grinding are described as follows:

$$X_{RCO_2} = E_{cM} \cdot J_{KCO2} \tag{4}$$

where:

E_{cM} – total energy consumption of grinding machine during grinding mass of biomass m_B, kWh,

J_{KCO2} – emission of carbon dioxide for production of electric energy from coal, $kgCO_{2eq} \cdot kWh^{-1}$

In this case, environmental costs were assumed as total energy consumption E_{cM} for biomass grinding. Taking into account the above and dependencies (3) and (4), the sustainable CO_2 emission index will take the form

$$W_{ZCO_2} = \frac{X_{BCO_2} - X_{RCO_2}}{E_{cM}} = \frac{m_B \cdot \sum_{i=1}^{n} \left(J_{AiCO2} \cdot W_{iB} \cdot q_i \right) - E_{cM} \cdot J_{KCO2}}{E_{cM}} \tag{5}$$

2.2. Conditions of experimental model verification

2.2.1 Test stand

Mathematical model of sustainable CO_2 emission index for grinding process in biomass processing chain was developed to implementation in self-regulating control grinding system, which include five-disc mill.

2.2.2 Comminuted biomass

The study involved samples of corn and rice, which properties are shown in table 1. Corn is widely used in energy sector, especially in biogas production. Rice, as plant with greatest cultivation area has big potential to use in energy production. Both comminuted grains can

be a good substitute for coal considering their relatively high heating values. For the samples the CO_2 emission during combustion process was specified.

Table 1. Characteristics of tested materials.

	Rice		**Corn**	
Humidity (%M)	13.600		9.378	
Average size of particles D_{80} (mm)	2.18		7.85	
Calorific value of size class (kWh·kg^{-1})	0-630 μm	3.97	0-500 μm	3.91
	630-1250 μm	3.93	500-1250 μm	4.05
	1250-2000 μm	3.89	1250-2000 μm	4.02
	>2000 μm	3.85	>2000 μm	3.96
Unit CO_2 emission for the *i*-th size class of biomass (kg·kWh^{-1})	0-630 μm	42.05	0-500 μm	45.68
	630-1250 μm	34.27	500-1250 μm	51.62
	1250-2000 μm	69.84	1250-2000 μm	55.37
	>2000 μm	105.73	>2000 μm	63.07

2.2.3. Comminution process conditions

Table 2 presents exemplary settings of angular speed of the disc for which it was examined what effect they exert on the values of a sustainable CO_2 emission index.

Table 2. Exemplary settings of the five-disc mill control parameters

| Research program	No. of configuration	$\Delta\omega$ rad·s^{-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}
I	1	5	20	25	30	35	40
	2	10	20	30	40	50	60
	3	15	20	35	50	65	80
	4	20	20	40	60	80	100
II	1	20	100	80	60	40	20
	2	15	80	65	50	35	20
	3	10	60	50	40	30	20
	4	5	40	35	30	25	20

During the grinding, parameters such as: the power demand for each disc and the weight of the product in the basket, were recorded for each disc speed configuration.

3 Results and discussion

Grinding processes carried out in particular research programs were subjected to emission assessment. For this purpose, for each case, the values of the sustainable CO_2 emission index were determined based on dependence (5).

When analyzing the variability of a sustainable CO_2 emission index, it should be noted that the desired condition is to reduce energy consumption for grinding E_{cM} and increase ecological benefits ΔB_{CO_2}, ie. replacing CO_2 emissions from coal with CO_2 emissions from biomass combustion. In this case, the value of the proposed index should increase. When comparing the grinding processes, the more favorable in terms of emissions will be the one for which the sustainable CO_2 emission index will assume higher values.

On the basis of the results, it was found that the best in terms of emissivity, both in the case of rice and maize grinding, were settings II4 and II3 of the angular speed of the grinder discs (Fig. 1). The least advantageous were the settings of I4 and I3 (Fig. 1.). It was noticed that better results in terms of emissivity were obtained for the research program II, in which the angular velocities of the discs decreased from the first to the last disc.
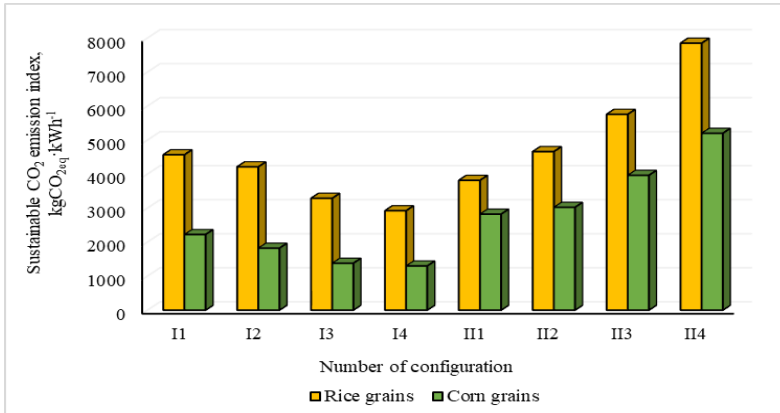
Fig. 1. Results of sustainable CO_2 emission index for each discs speed configuration

The relationship between the sustainable CO_2 emission index and the angular speed increase for the tested angular speed settings of the grinder discs was described with a high matching ($R^2 > 0.92$) with the linear model (Fig. 2). The obtained linear relationships indicate that the value of a sustainable CO_2 emission decreases with the increase of angular speed on the grinder discs.
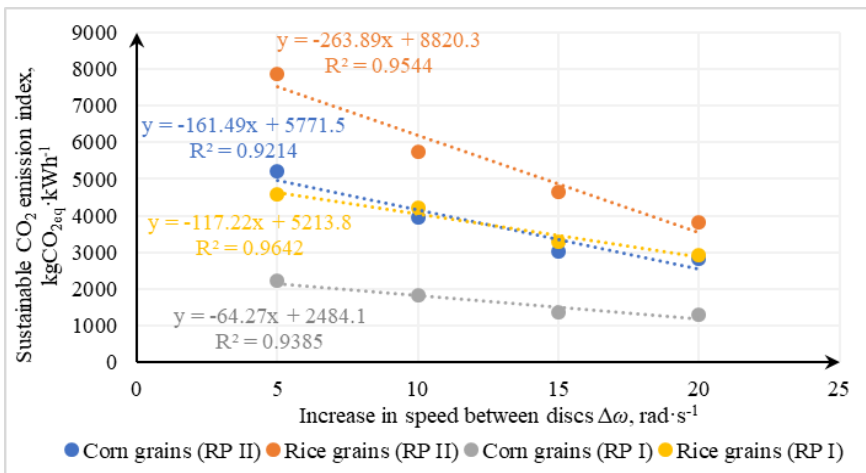
Fig. 2. Sustainable CO_2 emission index in dependance of increase in speed between discs; RP I – research program I, RP II – research program II (see table 2.)

4 Conclusions

The aim of the work, which was to develop a mathematical model of a sustainable CO_2 emission index for ecological assessment of the grained biomass grinding process was

achieved. The methodology for assessing the emissivity of the grinding allowed the measurable assessment of the process taking into account its energy consumption and emissivity. Analysis of the sustainable CO_2 emission index allows to state that:

– the sustainable CO_2 emission index of rice and maize grinding on a five-disc mill depending on the angular speed increase on discs $\Delta\omega$, can be described with high adjustment using a linear model (Fig. 2.),
– it was observed that the sustainable CO_2 emission index increases with the increase of the $\Delta\omega$ value,
– from the point of view of emissivity, it is better to grind at lower angular velocities of the discs.

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