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Application of inverse analysis in electromagnetic grinding of brown coal to obtain an optimal particle size distribution – a heuristic approach

Michał Gandor[1], Krzysztof Sławiński[1], Krzysztof Knaś[1], Barbara Balt[1], Wojciech Nowak[1,2]

[1] *Częstochowa University of Technology, Institute of Advanced Energy Technologies Dąbrowskiego 73, 42-201 Częstochowa, Poland*
e-mail: mgandor@fluid.is.pcz.pl, kslawinski@fluid.is.pcz.pl, kknas@fluid.is.pcz.pl, bbalt@fluid.is.pcz.pl

[2] *AGH University of Science and Technology, Al. Mickiewicza 30, 30-059 Kraków, Poland*
e-mail: wnowak@is.pcz.czest.pl

This paper presents the research results of milling process optimization in the electromagnetic mill to obtain the predetermined particle size distribution of brown coal. Because of an important role of brown coal in Polish energy industry (power plants produce 9433 MW of electrical power from brown coal, which corresponds to about 34% share in total fuel usage structure of energy industry in Poland – 2nd quarter 2013 [1]), there is a great need to look for and develop highly efficient methods of its mining, valorisation and low-emission combustion alongside with CO_2 capture technology. This paper proposes, as one of the methods of adapting low-rank coal to being utilized in modernized and newly built plants, the process of simultaneous grinding and drying in an electromagnetic mill system. This method is energy efficient and what is more significant it reduces the space required for its adaptation, thanks to electromagnetic mill's compact installation design. It is essential to obtain the desired characteristics of the product through the adequate control of the processes. Major concern of this case study was focused on determination of optimal grinding parameters in the electromagnetic mill in order to obtain two products of a desired size distribution (1–6.3 mm for application in fluidized bed boilers and 0–315 μm for boiler burners). The authors presented some theoretical considerations of the mechanisms and physical phenomena occurring during a fragmentation of solid particles as well as the literature review of the subject. The process complexity level, taking place in the active area of electromagnetic mill, involves the influence of particle – milling rod and particle – particle interactions as well as the volume of milling rods or coal particle residence time on the size distribution of the product. All of the mentioned factors account for nonlinearity of the problem and make the conditions difficult to rescale. Hence, a heuristic approach to inverse problem was chosen to analyse the differences between the desired and obtained particle size distributions. The examinations concerned grinding parameters such as total amount of rods (volume-based) and rod sizes (single and multi-size combinations of milling elements) were conducted. Equivalent samples of Polish brown coal with a particle diameter size ranging from 0 to 10 mm were chosen as an investigated material. Influence of the total volume of rods was examined using three amounts: 100 ml, 150 ml and 200 ml. Two grinding aid sizes were chosen in the form of ferromagnetic rods: fine rods of the size of 10×1 mm and coarse rods of the size of 20×2 mm.

Keywords: milling, brown coal, particle size distribution, optimization, electromagnetic mill.

1. Introduction

Poland is among the countries with significant brown coal deposits. In 2012, the production of brown coal reached almost 80×10^6 Mg, of which 67.5×10^6 Mg constituted for energetic coal. Brown coal accounts for one third of present basic fuels. With the rising demand for electricity and thus the need for increased electric energy production (38 GW of power installed in 2013 and a predicted 60 GW in 2030) the significance of brown coal will remain at high level [1, 2]. An increasing interest in this fossil is also justified by the expected period of its mining, which is considered to be about 300 years, in comparison with 200 years for a primary energy carrier – hard coal [2]. In many countries, including Poland, research is conducted on a large scale related to the effective utilization of brown coal in energy sector and also on its valorisation and protection of its deposits [3]. Several problems however accompany the utilization of brown coal associated with the characteristics of this fuel that need to be taken into account when modernising old and creating new technologies. From the technical point of view, the biggest distinction between coals of different ranks is the amount of moisture and ash content, which has a significant impact on the energy efficiency of the boiler as well as some maintenance problems that may occur during the preparation, transportation and combustion. Elevated moisture and ash content cause a decrease in energy density of the fuel, which in turn reduces or excludes the possibility of economically justified long distance transport. Furthermore, an increased flue gas volume accompanying the combustion of brown coal has negative ecological consequences. Adding brown coal to higher-rank coals, allows to lower the NO_x emissions by introducing volatile components in the vicinity of combustion zone [4]. Research is also conducted on coal gasification in pressure reactors and on underground gasification in situ. Coal milling plays an important role in coal preparation for utilization in various technologies. Grinding and especially selective grinding is one of the basic methods for solid fuel adaptation in the "clean coal technology" program. The goal of this program is to diminish the negative impact of coal combustion on the environment. Four main methods are used: pre-combustion (modification of fuel prior to its combustion), advanced combustion (modification of combustion process, for example, with innovative boiler construction), advanced post-combustion (flue gas treatment) and conversion (gasification, pyrolysis, etc.) [5]. For pre-combustion, the usage of coal blends of desired properties and selective grinding are considered in order to clean the fuel from high contents of sulphur, which occurs in coal as pyrite. Deep coal processing is performed by fine-milling and removing small particles of waste rock. One of the methods of advanced combustion is using a blend of low and high-rank coals in order to obtain lower NO_x emissions. Air-dispersed finely ground brown coal also seems to be an interesting and less expensive alternative for fuels used in boiler burners such as fuel oil or mazout. Fine milling of coal allows for lower loss on ignition – smaller particles burn faster and fuel conversion is greater than that of coarse particles, which in turn enables for more compact and effective boiler design. For the methods based on conversion it is also important to obtain a desired size of particles, the example of such methods is the utilization in pressure fluidized gasification, this is one of the technologies developed under the National Centre for Research and Development (Narodowe Centrum Badań i Rozwoju – NCBR) Strategic Research Programme "Advanced technologies for energy generation", in which the authors actively participate. Research has shown that parameters like volatile matter initiation temperature, peak reactivity value, temperature of char burnout, total burnout time or temperature of self-heating are influenced not only by the size distribution of particles but also by the grinding method used to obtain these particles [4]. Comminution is a highly energy-intensive process, the power consumption according to the literature can extend from 1 to about 15 kWh/Mg [6, 7]. The range is wide and it is affected by factors like coal grindability, level of moisture or energy required for drying of the feed material and product separation. Total power consumption of grinding process is higher, when efficiency of the machines is considered.

The operation of a prototype electromagnetic mill installation for grinding and drying of solid fuels proposed by authors is based on a rapid movement of small milling rods, which is forced with an alternating electromagnetic field. In this technology, a conversion of high electric energy into mechanical energy occurs and the heat generated by the milling rods is used to reduce moisture in the material. The milling rods move chaotically inside the chamber, hitting the fuel particles, each other and also the walls of the milling chamber. So far, no accurate model exists for the phenomena accompanying electromagnetic grinding and a vast majority of parameters are obtained experimentally. Therefore, it is necessary to conduct an inverse analysis of grinding in an electromagnetic mill in order to determine the parameters allowing for an optimal particle size distribution of the product.

2. Comminution

Comminution is a process of reducing with externally applied destructive forces the size of solid bodies to produce smaller elements. The source of the force can be either mechanical or, more rarely, chemical. Mechanical forces acting on the particles of fuel are dependent on the technology used, in most cases several comminution mechanisms occur simultaneously. Because grinding is the effect of a combination of many processes, it is hard to perform this modelling. As in the case of many dispersed material technologies, the analysis of a path of a single particle in the milling area is difficult and the characteristics that are true for a particle can be false for the material in a macroscale. Therefore, it is common to make an estimation and to average those parameters. One of the most essential properties of milling coal is its grindability. It is a result of coal's hardness, strength and crystalline structure. Those features are affected by the rank of coal, its petrography and mineral matter content. There is no single reliable method of classification of coals on the basis of their grindability. One of the most common ways to measure coals grindability is the Hardgrove test. The value of Hardgrove index is determined via conducting a laboratory scale experiment, it does not though reflect the milling process in an industrial full-scale installation. The value of this index arranges different coals according to the "easiness" with which they are fragmented; however it does not give the information on the amount of energy needed to comminute the material. Many authors claim that the value of Hardgrove index is non-additive and it should not be used for estimating grindability of coal blends made from coals of significantly different Hardgrove index.

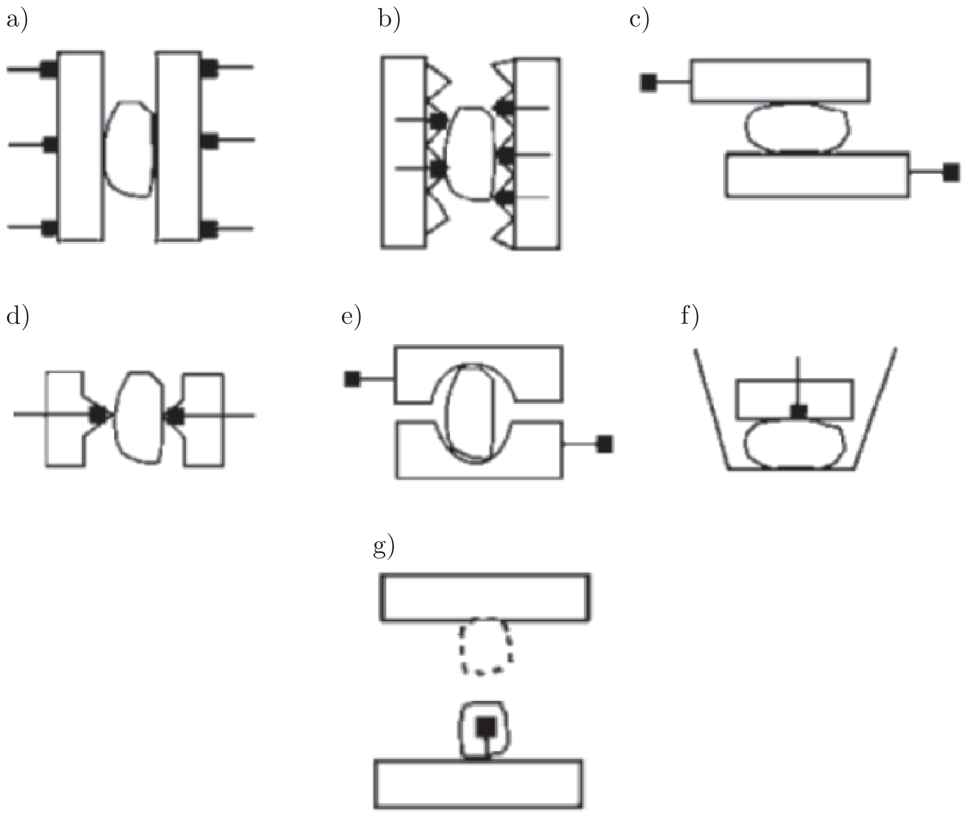

Fig. 1. Different mechanisms of comminution: a) crushing, b) breaking, c) attrition, d) lamination, e) shearing, f) mastication, g) hitting [8].

There are several theories linking grinding with power consumption, they have however some limitations and do not apply in all cases. Kick's theory specifies the energy needed for the fragmentation of particles with the sizes exceeding 1 mm, Bond's theory specifies the approximate energy needed for the fragmentation of particles in the size range of tens to hundreds of μm and Rittinger's theory concerns ultrasmall particles. Generally, the amount of energy required for fragmentation rises with decreasing of particle size and is proportional to the newly-created surface area. Some improvement of the comminution theory is the Shi-Kojovic model developed in 2007, which allows to estimate the energy required for grinding in a broad range of sizes (Hardgrove test is made for particles of the size 0.6–1.18 mm). Research on the influence of particle size and the energy of comminution showed that for low values of specific fragmentation energy, with the normalization of the Shi-Kojovic equation, there is a linear correlation between experimentally obtained Hardgrove index and specific energy of comminution. For deeper milling there is a need for larger energies, which can be estimated by the Shi-Kojovic model [9].

An important problem in case of grinding is the loss of energy for grinding of the particles which sizes are already in a desired range. This is essentially relevant in a case when the mill has limited possibility for particle separation in the process. In such situations it is crucial to separate particles of different granulation prior to milling or to modify the installation [7]. Additional problems are caused by the moisture content in fuel, which lowers the ability for grinding, causes the particles to stick to the grinding surfaces and increases the energy losses due to the deformation in non-elastic bouncing. Lack of an absolute information on the processes taking place inside the chamber of the electromagnetic mill (the influence of the magnetic field, interaction between milling rods and the material, the number of collisions, influence of the moisture loss, effect of the moisture in the feed material on coals grindability) predestinates the problem for being solved with the use of inverse analysis. Additionally, with so many unknown parameters, a heuristic approach for the problem was selected in order to omit the initial estimation of the fragmentation model and by analysing the initial conditions and the obtained results. The goal of the analysis was to describe the processes inside the mill that determine the particle size distribution of the product.

3. Design of the electromagnetic mill for grinding and activation of the material

Electromagnetic mill is a device for grinding of particulate matter of a maximal size of couple of millimeters with the use of small ferromagnetic grinding aid. Grinding rods are pushed with the

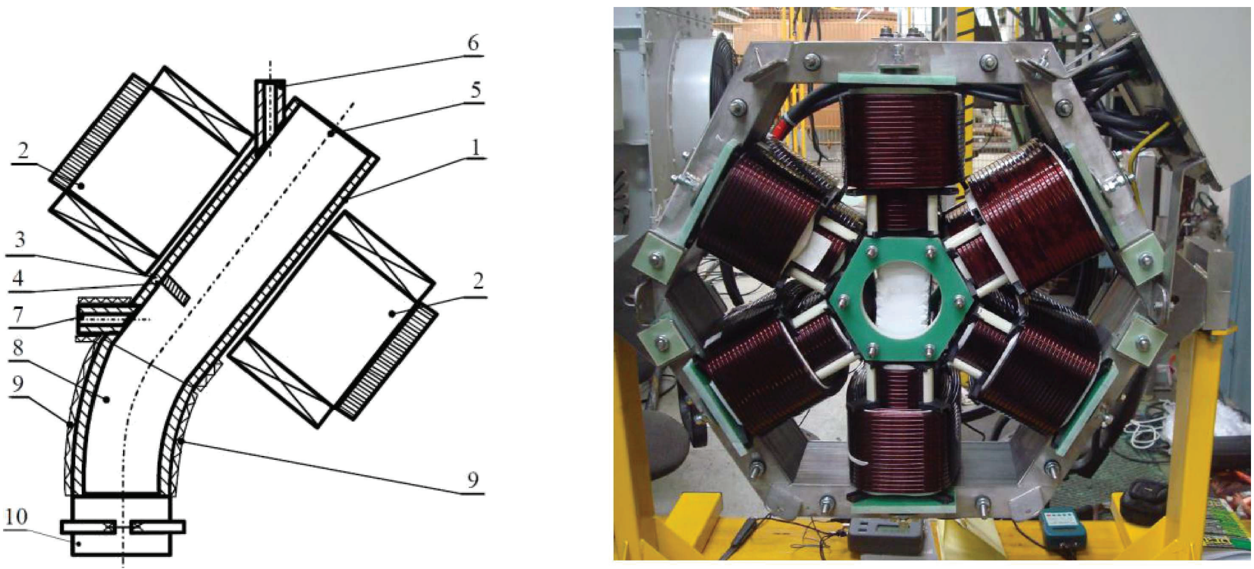

Fig. 2. Design scheme of the electromagnetic mill (left): 1 – milling chamber, 2 – inductor poles, 3 – stop, 4 – vapour transport holes, 5 – material inlet, 6 – grinding aid/gas inlet, 7 – vapour collection vent, 8 – product outlet, 9 – thermal insulation, 10 – fastener for a tight connection of the milling chamber with product container. Physical model of the inductor (right).

force exerted on them by an alternating electromagnetic field produced by the inductor. The field is created by salient poles of the inductor with a three-phase alternating current from a 50 Hz power grid. The main element of the electromagnetic device for grinding and drying of coal is the mill, which consist of two basic parts: milling chamber with grinding aid and a stator with salient field poles. The milling chamber is a non-ferromagnetic tube in which small ferromagnetic milling rods are rotating suspended in magnetic field. Those two elements create work area in which the feed material is subjected to mechanical, thermal and magnetic treatment. With the increasing magnetic induction inside the chamber, small grinding rods are forced to rotate and move faster and more chaotically. A ferromagnetic rod suspended in magnetic field becomes a magnetic dipole and is attracted by the field with certain force. Due to the small size of milling rods and optimized dimension proportions it is possible to gain high acceleration and to quickly obtain maximum velocity of the grinding aid. Because of the very high rotation speed, there is a very large amount of consecutive collisions of rods and fuel particles, which allows for much quicker process compared with the mills in which the period between impacts is extended.

Parameters influencing the operation of inductor, involving the geometry of the inductor, milling chamber as well as dimensions of grinding rods have been determined by mathematical modelling and were presented in the form of design methodology [10]. Research was conducted on a model with a milling chamber of the diameter of 100 mm.

4. Problem identification

The aim of this research was to establish the main parameters determining particle size distribution of the product (100–315 μm range for utilization as fuel in new generation coal dust burners and 1–6.3 mm used as fuel for fluidized bed boilers). Since at this stage of research no accurate model exists of the comminution process in an electromagnetic mill, very little information is available on the optimal amounts and sizes of milling rods and volume/weight ratios of grinding aid to coal. In theory, the usage of small milling rods should result in smaller particle sizes of the product. Electromagnetic mill is therefore especially effective in case of fine milling. The force exerted on grinding aid by magnetic field is dependent on the second power of the field induction magnitude in the vicinity of the milling rod. The induction in the neighbourhood of the rod in its axis is smaller when compared to milling rod – free region, so extensive amount of rods and their high density results in weaker induction in the milling chamber. The influence of the differently sized milling rod blends on the obtained particle size distribution of the product remained unexplored and it was also a subject of this research.

5. Experiments

During the experiments, two sizes of milling rods were used: 10×1 mm and 20×2 mm (length $\times$ diameter). Aspect ratio 10: 1 of length to diameter was dictated by calculations, which showed that for such dimensions the magnitude of the induced magnetic field as well as the efficiency of grinding is optimal. The amount of grinding aid in each test was 100 ml, 150 ml and 200 ml. The feed material used in the tests was brown coal, characterized by the parameters listed in Table 1.

For each test a constant volume of the feed material was used. Flow of the material was forced by gravity.

Tests were carried out using different volumes (100–200 ml) and different sizes of milling rods (10×1 and 20×2 mm) in order to compare the particle size distribution of the product with the particle size distribution of the feed material. This has resulted in a series of histograms which were used to determine the effect of the grinding aid on the quality of the final product in a form of fractions 0–315 μm and 1–6.3 mm.

Table 1. Physico-chemical parameters characterizing the sample of brown coal used in the study.

Parameter	Value
Received basis:	
Total moisture W_t^r [%]	51.14
Ash content A^r [%]	10.74
Total sulphur S_t^r [%]	0.91
Lower heating value Q_i^r [kJ/kg]	8555
Analytical basis:	
Moisture W^a [%]	9.15
Ash A^a [%]	20.04
Volatiles V^a [%]	38.28
Higher heating value Q_S^a [kJ/kg]	23330
Lower heating value Q_i^a [kJ/kg]	21091
Carbon C^a [%]	43.80
Hydrogen H^a [%]	4.65
Nitrogen N^a [%]	0.53
Total sulphur S_t^a [%]	1.77
Dry basis:	
Ash A_d [%]	23.08
Total sulphur S_t^d [%]	1.82
Volatiles V^{daf} [%]	45.93
Higher heating value Q_S^{daf} [kJ/kg]	19000

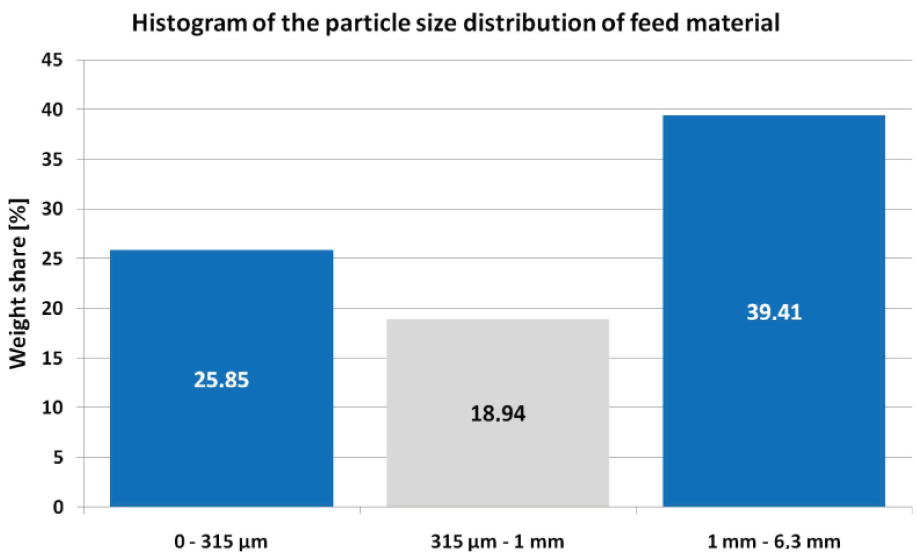

Fig. 3. Histogram of the particle size distribution of the feed material, blue colour – desired fraction, grey colour – the intermediate fraction.

6. Results and discussion

In this study, the 20×2 mm milling rods were used first.

Particle size distribution analysis of the product showed a slight reduction in the grinding of the coarse and intermediate fractions, respectively, 4.33% and 3.91%, and the increase in the share

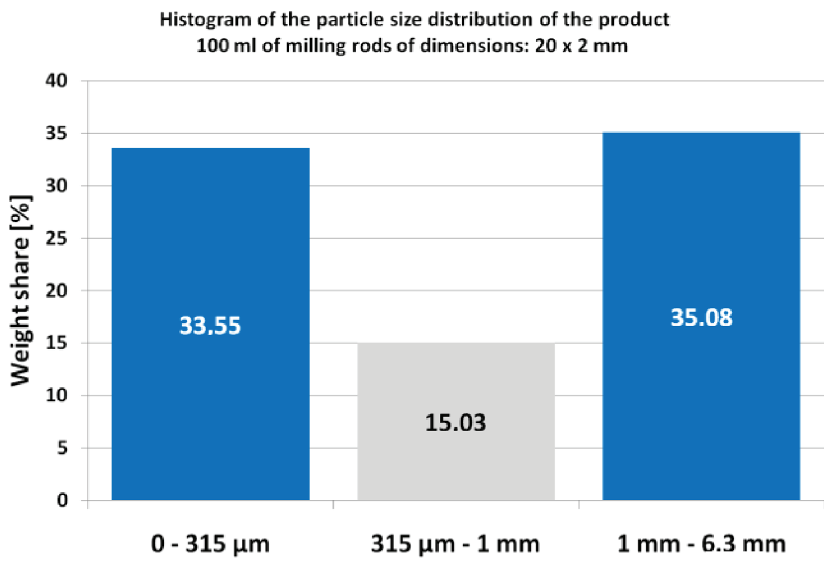

Fig. 4. Histogram of the particle size distribution of the product, the blue colour – desired fraction, grey colour – the intermediate fraction. Grinding with 100 ml of milling rods of dimensions 20×2 mm.

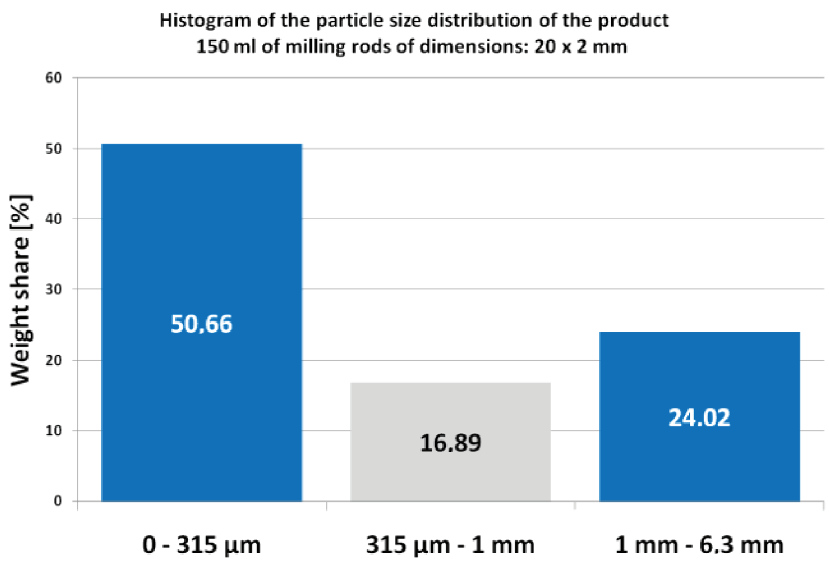

Fig. 5. Histogram of the particle size distribution of the product, the blue colour – desired fraction, grey colour – the intermediate fraction. Grinding with 150 ml of milling rods of dimensions 20×2 mm.

of fine fraction from 25.85% to 33.55% by weight. It was found that a low efficiency of grinding carried out in this manner can result from a too low volume of the grinding aid with respect to the feed material and milling chamber volume.

Increasing the amount of grinding media should result in further reduction of coarser fractions and dispensing the weight loss between the finer fractions. After increasing the volume of grinding media from 100 to 150 ml, a clear decrease in the coarse fraction mass was observed. Part of the lost mass was found within the intermediate fraction, while the vast majority transferred to the fine fraction. As a result no satisfactory reduction of the intermediate fraction was obtained, and it was found that the milling rods of the size of 20×2 mm may interact mostly with coal particles larger than 1 mm. It was acknowledged that a more favourable effect cannot be achieved by further increasing the amount of grinding aid and it is necessary to use finer milling rods for stronger impact on sub 1 mm particles.

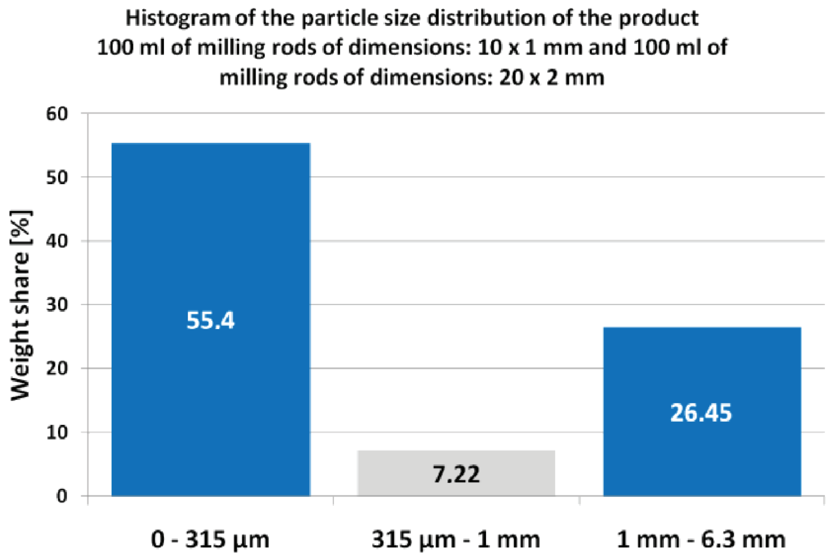

Fig. 6. Histogram of the particle size distribution of the product, the blue colour – desired fraction, grey colour – the intermediate fraction. Grinding with 100 ml of milling rods of dimensions 10 × 1 mm and 100 ml of milling rods of dimensions 20 × 1 mm.

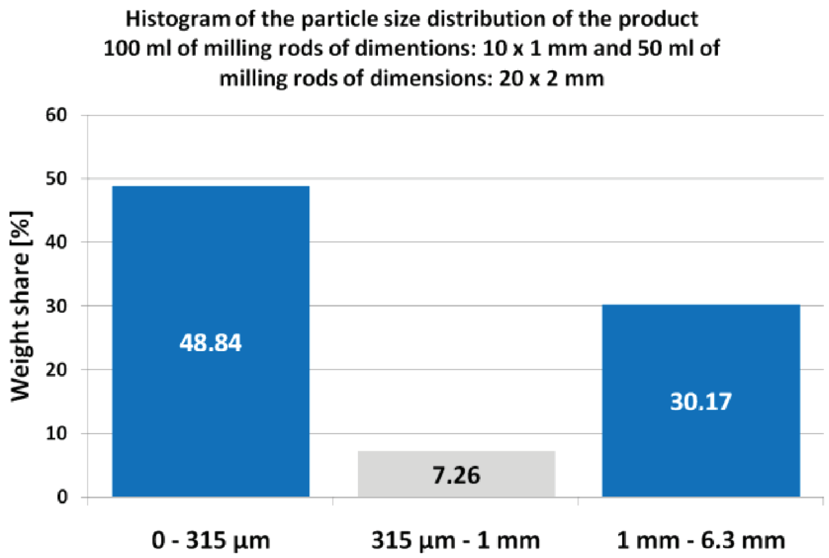

Fig. 7. Histogram of the particle size distribution of the product, the blue colour – desired fraction, grey colour – the intermediate fraction. Grinding with 100 ml of milling rods of dimensions 10 × 1 mm and 50 ml of milling rods of dimensions 20 × 2 mm.

After the change of grinding aid to a blend of 50: 50 of milling rods with dimensions of 20 × 2 mm and 10 × 1 mm with a total volume of 200 ml, there was a significant decrease in the share of the intermediate fraction from 16.89% in the case of using only coarse milling rods to 7.22% in the case of using a 50: 50 blend. As expected, the rods of the size of 10 × 1 mm more effectively comminuted particles with the size less than 1 mm. Additionally, a significant share of ultra-fine milling occurred in the process, resulting in more than 55% content of fraction 0–315 µm. To obtain information on mutual interactions of different sizes of milling rods in the grinding process, further studies were performed with the increasing share of the 10 × 1 mm milling rods for both total volumes of 150 and 200 ml. The reduction of the amount of 20 × 2 mm milling rods allowed to keep a larger share of fraction 1–6.3 mm. Furthermore, with an increase in the amount of 10 × 1 mm milling rods

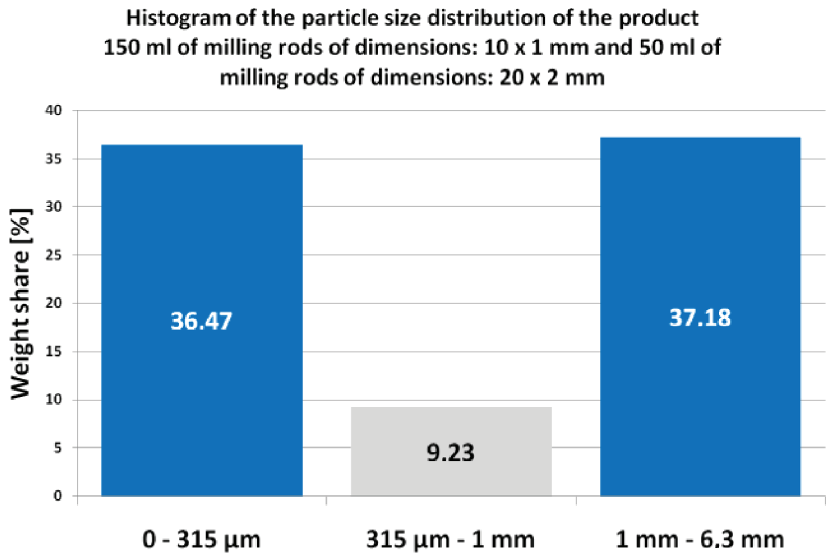

Fig. 8. Histogram of the particle size distribution of the product, the blue colour – desired fraction, grey colour – the intermediate fraction. Grinding with 150 ml of milling rods of dimensions 10 × 1 mm and 50 ml of milling rods of dimensions 20 × 2 mm.

up to 150 ml, a minor effect on the reduction of the coarse fraction was registered with a small reduction of the intermediate fraction. The effect of 10 × 1 mm milling rods on milling process was observed for each ratio of the mixture, changing only the ratio between fine and coarse fractions of the product. At this stage, it was found that the presence of small rods (10 × 1 mm) is necessary to reduce the 0–315 µm fraction. Effect of 20 × 2 mm rods on the reduction of 0–315 µm fraction is small, and their impact on grinding process is mostly observed for particles greater than 1 mm. To further reduce the share of the intermediate fraction, it was decided to carry out further studies using different amounts of milling rods with dimensions of 10 × 1 mm.

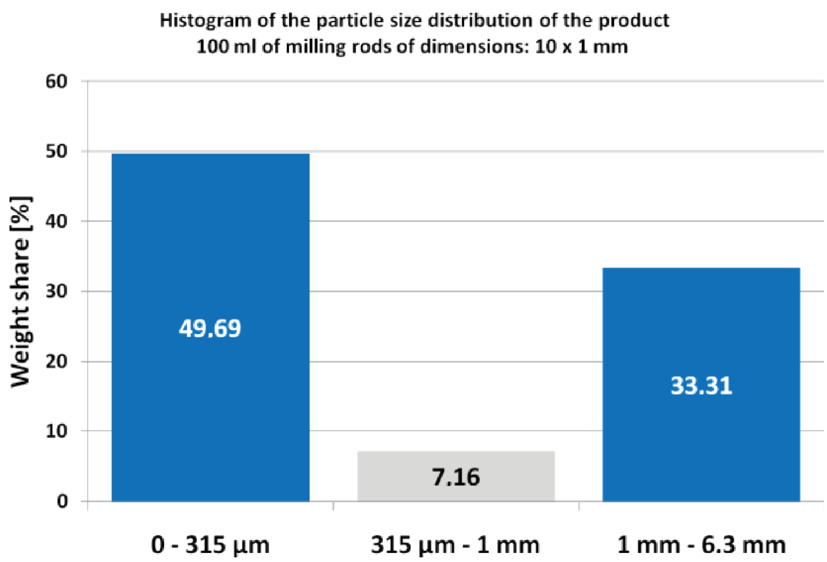

Fig. 9. Histogram of the particle size distribution of the product, the blue colour – desired fraction, grey colour – the intermediate fraction. Grinding with 100 ml of milling rods of dimensions 10 × 1 mm.

As presumed, the lowest share of the intermediate fraction (from 7.16 to 3.43%) was obtained in the case of milling with 10 × 1 mm rods. In addition, the share decreased with an increasing

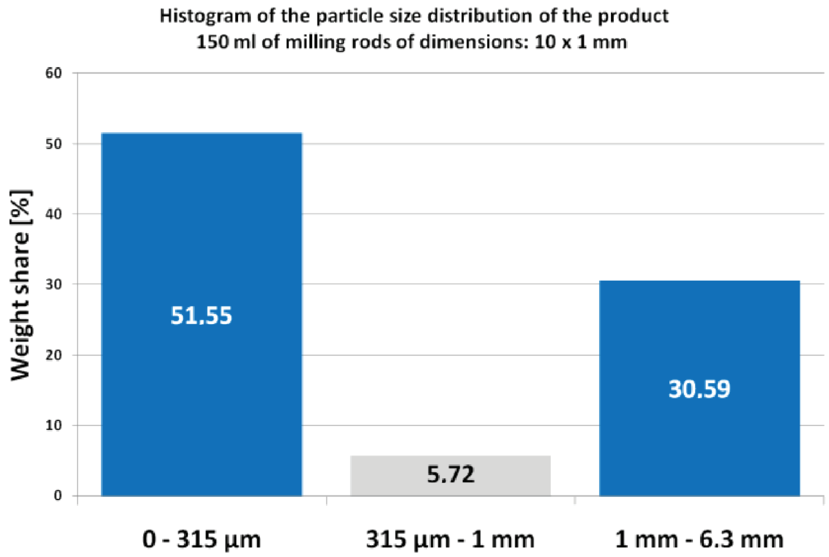

Fig. 10. Histogram of the particle size distribution of the product, the blue colour – desired fraction, grey colour – the intermediate fraction. Grinding with 150 ml of milling rods of dimensions 10×1 mm.

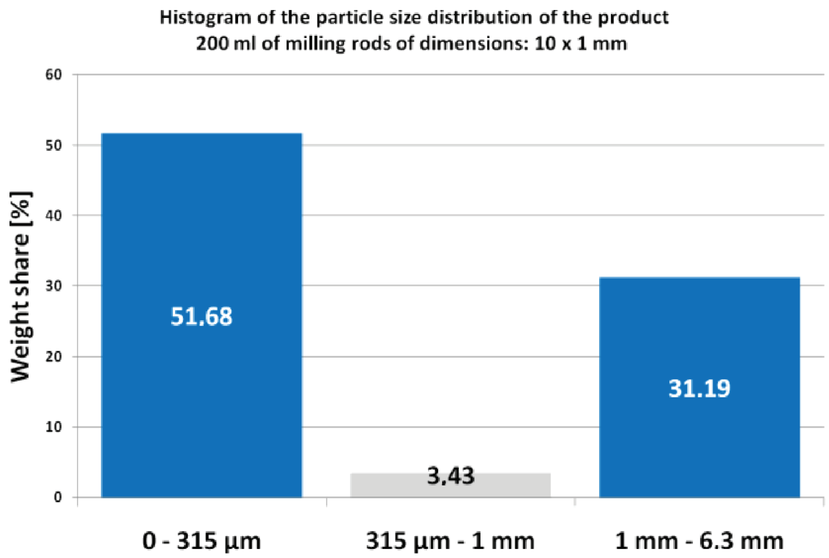

Fig. 11. Histogram of the particle size distribution of the product, the blue colour – desired fraction, gray colour – the intermediate fraction. Grinding with 200 ml of milling rods of dimensions 10×1 mm.

volume of grinding aid with respect to the volume of the chamber. In each case, similar proportions between fractions were obtained, namely: about 50% of the 0–315 µm fraction, about 30% of the 1–6.3 mm fraction and 3 to 7% of the intermediate fraction – which should be reground. This results in using 200 ml of 10×1 mm grinding aid, which is the most preferred since it significantly lowers the energy required for refragmentation of the intermediate fraction in the next grinding cycle. Nature of the influence of fine grinding aid on the coarse fraction is also different, when compared with 20×2 mm rods. In the case of coarser grinding aid, its total volume influences the fragmentation of the coarse fraction, and this effect increases significantly above 100 ml of grinding aid. For the 10×1 mm rods, no such significant impact was observed, whereby it can be concluded that this type of grinding aid interacts weaker with coarse particles and a few percent reduction in coarse fraction may be due to crushing occurring in the screw feeder and due to the interactions between the particles of fuel – the collision and mutual attrition.

7. Conclusions

During the research to obtain an optimum particle size distribution of electromagnetically ground lignite, a series of tests were conducted, using different sizes (10 × 1 mm and 20 × 2 mm) and various volumes of grinding aid (100, 150 and 200 ml). The studies have shown that it is possible to grind the feed in such manner that it is possible to obtain a minimum amount of intermediate fraction, which in turn allows for energy savings from less material requiring regrinding. It has been found that grinding aid of the size of 20 × 2 mm strongly influences the >1 mm fraction and by controlling its volume it is possible to obtain greater amounts of 1–6.3 mm fraction in the product. In addition, the use of milling rods of that size allows to obtain a significant share of 0–315 μm fraction. The relatively weak effect of the milling aid size on reducing the share of the intermediate fraction is still not fully explained. An increased amount of the intermediate fraction as compared to that obtained with finer grinding aid may result from the transfer of weight of the >1 mm particles into smaller fractions as a result of their fragmentation. Smaller grinding aid can effectively grind particles in the range of 315 μm – 1 mm and therefore reduce the amount of the intermediate fraction. In each case, an ultra-fine milling was observed and the size of grinding aid defined the upper limit of the size of affected coal particles. The use of finer grinding aid can produce more homogeneous, fine-grained product, while the coarser milling rods are capable of fragmenting larger particles, resulting in both linear and more uniform particle size distribution of the product. A suitable combination of two or more sizes of grinding aid in a total volume considered optimal (200 ml), allows to achieve the desired product properties.

Acknowledgment

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