11. Vainer, L. G., Flusov, N. I. (2013). Geometrical modification of the face-grinding wheels in the dressing. Vestnik Tihookeanskogo gosudarstvennogo universiteta, 17. Available at: http://science-bsea.bgita.ru/2013/mashin_2013_17/vainer_geometr.htm
12. Kalchenko, V., Kalchenko, V., Sira, N., Yeroshenko, A., Kalchenko, D. (2020). Three-Dimensional Simulation of Machined, Tool Surfaces and Shaping Process with Two-Side Grinding of Cylindrical Parts Ends. Advanced Manufacturing Processes, 118–127. doi: https://doi.org/10.1007/978-3-030-40724-7_12
13. Kalchenko V., Kalchenko V., Slednikova O., Kalchenko D. (2016). Modular 3D modeling of ends bilateral grinding process by wheels with conical calibrating sections. Scientific Journal of the Ternopil National Technical University, 4 (84), 82–92. Available at: https://visnyk.tntu.edu.ua/pdf/84/337.pdf
14. Kalchenko, V., Kalchenko, V., Kalchenko, O., Sira, N., Kalchenko, D., Morochko, V., Vynnyk, V. (2020). Development of a model of tool surface dressing when grinding with crossed wheel and cylindrical part axes. Eastern-European Journal of Enterprise Technologies, 3 (1 (105)), 23–29. doi: https://doi.org/10.15587/1729-4061.2020.202441
15. Li, H. N., Axinte, D. (2016). Textured grinding wheels: A review. International Journal of Machine Tools and Manufacture, 109, 8–35. doi: https://doi.org/10.1016/j.ijmachtools.2016.07.001

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IMPROVING THE EFFICIENCY OF THE COAL GRINDING PROCESS IN BALL DRUM MILLS AT THERMAL POWER PLANTS

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Ensuring the reliable operation of the dust fuel preparation system at thermal power plants (TPP) is a topical issue since it determines the energy strategy of any country that fires coals for thermal energy production. This unit is one of the most energy-intensive units in TPP. Those systems are outdated, poorly automated and high energy-intensive. Furthermore, they must ensure efficient and safe operation of the facility while being environmentally friendly. The current work focuses on the process of grinding coals in ball drum mills for further pulverized combustion. An experimental study was performed in order to determine the main factors (rotational speed of the drum mill, the degree of loading with the grinding balls, and the velocity of the supplied air) that affect the efficiency of the fuel preparation system. The obtained experimental data and performed mathematical modeling resulted in regression equations describing the energy performance of the mill. Three regression equations for mill productivity, power consumed, and specific surface area of the final product were obtained and validated. The study reveals that the lowest specific energy consumption is achieved when the relative rotational speed of the mill is between 0.81 and 0.87; the weighted average diameter of the balls ranges from 33.5 up to 34.5 mm; the load factor of the grinding media ranges from 0.325 up to 0.335, the supplied air velocity is between 0.2 and 0.3 m/s. The proposed methodology allows adjustment of the operating parameters of the grinding process to achieve the lowest energy consumption. The power consumption for the preparation can be reduced up to 5 % for the selected operation mode of the grinding facility

Keywords: drum ball mill, coal grinding, efficiency improvement, thermal power plant, regression analysis

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1. Introduction

Worldwide, TPPs are facilities that are used for the simultaneous production of thermal and electric energy. Different types of primary energy carriers such as natural gas, coals, biomass are used to run facilities. Some of them are directly used but the others must be initially processed before combustion. The fuel preparation process is energy-intensive, which results in an increased final energy price. Following this, to reduce final costs for energy production, mechanisms are being sought to improve the energy efficiency of each unit of the plant.

The possibilities of using solid fuels, in particular coals, in thermal power plants are far from being exhausted at present. In addition, due to the significant increase in the price of natural gas, the possibility of fuel base change in TPPs seems difficult to implement.

Coal is considered the second most important primary energy source in the world after fuel oil, as it provides about a quarter of the world's energy needs. Many countries of the world have coal reserves, and the average supply of coal is about 230 years. The Republic of Kazakhstan, which has huge reserves of this type of fuel, according to some forecasts, will be provided with it for more than 300 years [1].

At present, there are so many TPPs worldwide working on coals and using inefficient technology for grinding fuels. Almost all of the countries in the Former Soviet Union use similar fuel grinding technology. Due to low energy prices over the last few decades, no attention has been paid to the share of energy used in coal preparation. Nowadays, this fuel preparation system mostly affects the final price of energy produced.

Much of the research examines single parameters affecting the energy efficiency of the coal grinding system, while there is still no information for a comprehensive assessment.

2. Literature review and problem statement

Depending on the type of coals and the process of their combustion, the specific energy consumption for coal grinding at various TPPs range from 14.45 to 55.57 kWh/t. High energy needs refer to fuels with high resistance to grinding, low volatiles yield (less than 15 %), and the presence of liquid ash removal [2]. The study reveals that in recent decades, the share of volatiles in coals, as well as liquid ash, grows leading to increased energy consumption for grinding. A change in the composition of the raw material is the reason for the increased consumption of energy for grinding, which will affect all thermal power plants running on ball drum mill grinding systems. In [2], it is stated that this share of energy is classified as very significant compared to the modern ones. Since investment costs for the replacement are very significant, new methodologies and approaches for improving the efficiency of single items in the systems have been sought in this study. Different approaches for the analysis of the operation of fuel preparation systems at TPPs are presented in [3]. A thermodynamic analysis was performed to determine the efficiency of the fuel preparation system. The results are not supported by experimental results, and they have limited practical application.

The efficiency and reliability of the equipment for pulverizing power plants mostly depend on the physical and mechanical properties of the processed fuel and its further combustion.

Coal dust prepared in drum mills must have a polydisperse structure that meets the needs of the specific thermal power plant and must comply with the following important indicators such as fineness (R_{90}), average dust particle size (x), specific dust surface (S), and others.

In [4], the impact of the drum length to diameter ratio and also particle filling rate in the process of segregation of particles in a rotating drum is presented. The outputs from the study showed that short and long drums can be successfully used for the separation of the raw material (coals) both in radial and axial directions. This leads to better final grinding of the raw material but still, single parameters have been observed. The disadvantage of [4] is that no mathematical model is presented to determine different waterfall modes of the material in the drum in terms of the diameter of the balls. In addition, the relationship between the size of the balls and the size of the raw material is not specified.

Mathematical modeling is successfully used to optimize the performance of the ball drum mill when grinding brown coals [5, 6]. The segregation index provided in [5] is a result of the experimental study for three different diameters of the drum mill as well as three particle sizes. The amount of volatiles and ash content have a significant impact on the distribution in a ball drum mill, respectively for fuel grinding, and this was not discussed in this paper. In [6], both grinding and transportation processes are modeled with respective equations. A close look at the equations reveals that energy consumption for grinding is contrariwise proportional to air consumption. The error between experimental and numerical data amounted to ±10 %. The paper presents the impact of two main parameters on mill productivity. However, there are other parameters that must be considered in terms of the entire unit efficiency. No other parameters influencing the grinding process are also considered.

The degree of grinding in the drum can be improved by knowing the solid particles' pathlines in the drum or their collision with the wall. The performed CFD study with the adopted Eulerian approach mechanism showed that at a high rotational speed of the BDM, the impact of the specularity (specular reflection) and restriction coefficient are the most significant [7]. The results show that the specularity and restitution coefficient mostly affect the wall of the ball drum mill. Still, only single operational parameters have been analyzed in terms of the grinding process.

The methodology of determining the power consumed by the ball drum mill electric motor in terms of ball load and mill grinding capacity is presented in [8]. One of the conclusions is that the degree of filling the drum with balls significantly affects the grinding capacity of the mill. The size of the balls and rotational speed were not observed and discussed as the significant parameters of the grinding process.

The mechanism of the total energy can be successfully used in terms of the evaluation of crushing energy [9]. The different energy distribution in a BDM was due to different ball sizes. The Monte-Carlo method was used to predict the total regional energy distribution in a drum mill. The study is interesting to predict distribution in a ball drum mill but still not so useful to predict the amount of energy (specific energy consumption) for fuel grinding.

In recent studies, computer modeling has been used to visualize the behavior of the balls in a ball drum mill. A 3D modeling was proposed as a mechanism for an efficient and convenient way of feeding the mills with balls. In [10], it was found that the broken energy is in relation with the concentration of the balls in a ball drum mill. As a disadvantage of the paper, it can be pointed out that the distribution of balls by size in the drum is not considered. The energy exchange device proposed in [11] uses the pre-grinding of coals. Still, the energy consumption process is considered only in terms of the balls in a ball drum mill. There is also no information about the details of the performed experimental study.

The visual representation can be successfully used to improve the design of the grinding facility. Moreover, the theoretical interpretation of factors affecting the quality and productivity of the BDM is presented in [12]. The drawback of the study is that the results have not been validated and the reliability of the obtained dependencies is doubtful.

Based on the performed literature review, it is quite clear that scientific studies in this area are limited where a comprehensive approach to the parameters affecting the fuel grinding must be sought.

3. The aim and objectives of the study

The aim of the study is to determine the significant parameters improving the energy efficiency of the coal grinding system that uses an individual closed circuit for preparing coal dust. This will allow managing the grinding process in the most effective way in terms of the TPP needs. Also, this will enable to determine the optimal performance of the ball drum mill (improved energy efficiency) at different characteristics of the inlet material.

To achieve the aim, the following objectives are accomplished:

– to define all possible parameters that could affect the efficiency of the ball drum mill during fuel grinding;

– to analyze the significant parameters affecting the operation of the ball drum mill, and perform a multiscale experiment;

– to obtain regression equations for the significant parameters, and define the acceptable region of operation of the drum mill.

4. Materials and methods of research

The fuel grinding system subject of the study is part of the TPP-2, Temirtau. Currently, the TPP-2 is experiencing the following main problems:

– physical aging of equipment;

– decrease in the share of electricity generation based on thermal energy consumption;

– decrease in the efficiency of combined generation of heat and electricity, and deterioration of technical and economic indicators;

– reduced level of automation of technological process control;

– relatively high negative environmental impact;

– increased operational and maintenance costs.

One of the solutions to existing problems is to improve the efficiency of boiler units and auxiliary equipment of power plants, which include coal grinding mills [13].

The schematic diagram of the coal dust preparation system at the TPP-2 site is shown in Fig. 1. This system differs from the traditionally accepted individual scheme of dust preparation with an intermediate hopper for the ballast machine. The main distinguishing features of the solid fuel preparation system at the TPP-2 include:

– defrosting of fuel is carried out only in exceptional cases via hot air produced in a steam boiler at very low air temperatures (during winter season);

– in other cases, the coals are dried with hot air from the air heater of the steam boilers right before the fuel is supplied to the BDM, and thus the balance of the supplied primary and secondary air is disturbed;

– currently, preliminary stages of coal crushing are not provided, as a result, coal with large lumps (more than 25 mm) is fed into the mill.

The specified features of the TPP-2 mostly have a negative impact on the energy performance of the plant, for example, the gross efficiency of power boilers is about 86 up to 87 %, the specific power consumption for grinding is overestimated at 39.86 Wh per kg.

The identified drawbacks of the pulverization system show that the system does not allow the preparation of high-quality coal dust, since the ventilation mode has a significant impact on the operation of a ball drum mill. At low air velocities, dust removal is troubled, because of lower lift ability. Increasing the air velocity leads to a removal of large particles, electricity consumption for grinding is significantly increased, due to the lack of automation, the intermediate hopper is often filled, leading to the shutdown of the mills. Taking into account the noted shortcomings, the study focuses on the preparation of a mathematical model and proposes the methodology for the selection of important parameters affecting the operation of the BDM.

The proposed dust system is installed at each of the six boiler plants (TP-81) at the site of the TPP. For a single steam boiler (TP-81), two individual closed dust systems equipped with ball drum mills are mounted. The concerned dust preparation system at the TPP-2 contains the following items: an Sh-25A ball-drum mill (Sh-320/570), one mill fan of the BM 18A type with a capacity of 108 thousand m^3/h and a screw conveyor with a capacity of 60 t/h [11].

Coals from the bunkers are transported to the raw coal feeder (RCF), which controls the degree of loading of the mill. From the RCF, coal enters the throat of the Sh-25A mill, where hot, cold, and weakly heated air is supplied from an air heater, intended for drying coals [14] and transporting them throughout the dust system, dust hopper, and burners.

The process of drying coals in the mills is regulated by the weakly heated and cold air supplied through inlets of each dust system. The air recirculation system additionally facilitates the drying of coals. In the mill, the coals are grounded, and the mixture of dust and air is sucked into the separator through the outlet of the mill by a mill fan. In the separator, the reduction of the flow velocity is observed, as well as the direction change. Because of the swirl motion of the flow, large particles are separated from the flow. The particles trapped in the separator are discharged through the return pipe to the mill [15].

The gas-solid mixture from the separator is directed and enters into the cyclone tangentially. Coal dust particles due to centrifugal force deflect to the wall of the cyclone, losing speed, slide down the wall and crumble into the dust bin or reversible screw conveyor. Via the screw conveyor, the dust is sent to the dust bin located nearby the boiler. The air cleaned from solid particles is sucked out from the cyclone by a mill fan and supplied to the burners through the dust duct. From the industrial bunker, the dust is mixed with air supplied by the mill fan and blown into the boiler furnace [16].

The automatic regulation system [17] installed at the TPP-2 has poor design and is also weakly automated, as the process of regulating the operation and protection of the dust preparation system is performed by integrated block regulators [3]. The scheme of the dust preparation system with a ball drum mill is shown in Fig. 1.

At the same time, there are significant drawbacks in the operation of the power plant's fuel preparation system. Structural changes were made in the fuel path of the TPP-2 in Temirtau, JSC «AMT» due to the deterioration of the crushing equipment, which led to an increase in the energy consumption of the dust preparation process.

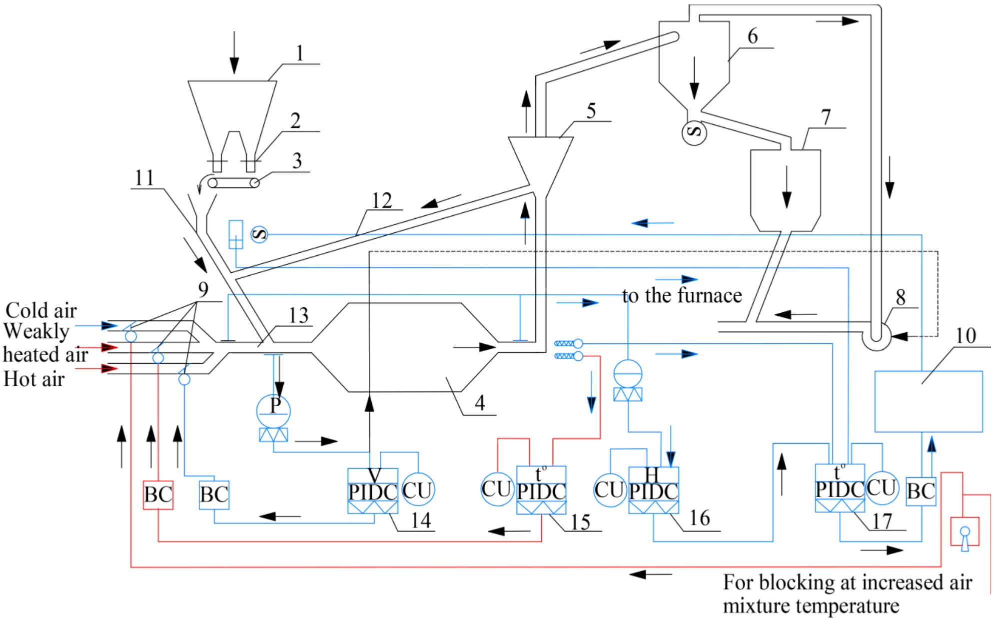


Fig. 1. Schematic diagram of the dust preparation system with a ball drum mill:
1 – raw coal hopper; 2 – gate of a tape feeder; 3 – belt fuel feeder (BFF); 4 – ball drum mill; 5 – separator; 6 – cyclone; 7 – dust bunker; 8 – mill fan; 10 – case of throttle converters; 9, 11, 12, 13 – dampers; 14 – vacuum regulator at the inlet of the mill; 15 – temperature regulator of the air mixture behind the mill; 16 – fuel regulator; 17 – regulator of an emergency cold air supplier; CU – manual control unit

In the classical scheme of the dust preparation system available at TPPs, a two-stage coal crushing system is used with a grinding coefficient kg > 1.1 [9]. The fractional composition of the Karaganda coals contains particles with average diameters from 40 mm to 3 mm. This heterogeneous composition of the coal particles when entering the mill complicates its operation, increases the grinding time, and leads to increased energy consumption for grinding [18]. Also, a destructive impact on the walls of the mill and grinding balls could be observed. In order to reduce this negative impact on the BDM, it was proposed to install a crushing press with a studded surface, which allows crushing large pieces of coal to the optimal size (25 mm). Such an approach could be applied in case of the absence of a preliminary crushing process at the TPP-2 [19].

The crushing press provides optimum crushing of oversized coal lumps due to the impact of its hydraulic hammer on the ramming plate. As a result of using this press, coal with a sieve size distribution from 25 mm to 3 mm will be supplied to the grid and hence to the receiving raw fuel hopper.

The main task of this study is to show the influence of the fractional composition of the fuel material at the inlet, which is further processed by the crushing device [19] on the final efficiency of the grinding process in a ball drum mill [17]. The efficiency of the proposed dust system will be verified also with the means of mathematical modeling that determines the quality of the grinding process.

The process of mathematical modeling will take into account the entire complexity of the technological process and meet a wide range of requirements for the high-quality production of coal dust [20].

To identify the main factors that could affect the grinding process in a ball drum mill [21] and search for their optimal values, an experimental study was performed by [22].

The experimental setup for studying the influence of operating parameters (drum speed, ball loading degree, etc.) on the efficiency of the grinding process is shown in Fig. 2. The experimental setup includes a ball drum mill that operates in a continuous mode.

An experimental ball drum mill with a standard size of 0.35×0.85 m, which was designed for the purpose of the study, is presented in Fig. 2. The control panel includes the «Start» button, which starts and stops the drum feeder, centrifugal fan, laboratory BDM. The power consumed is measured by the «OVEN» PChV102-1K5-A frequency converter. The multimeter (IMS-F1) allows measuring the parameters of the power supply network: voltage (*U*, V), current (*I*, A). The rotational speed of the mill is recorded with the «OVEN» TX01 frequency tachometer. The output current ranges from 4 up to 20 mA.

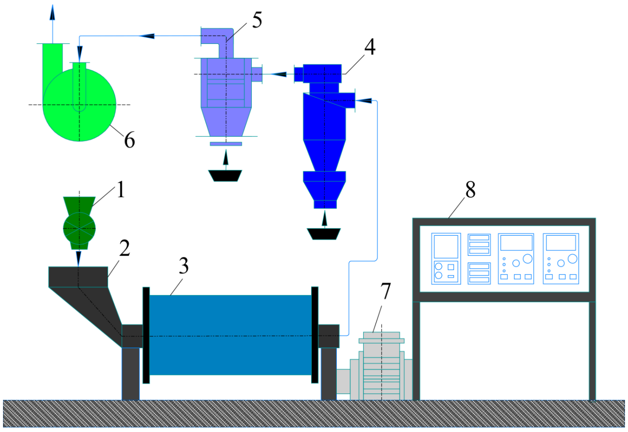
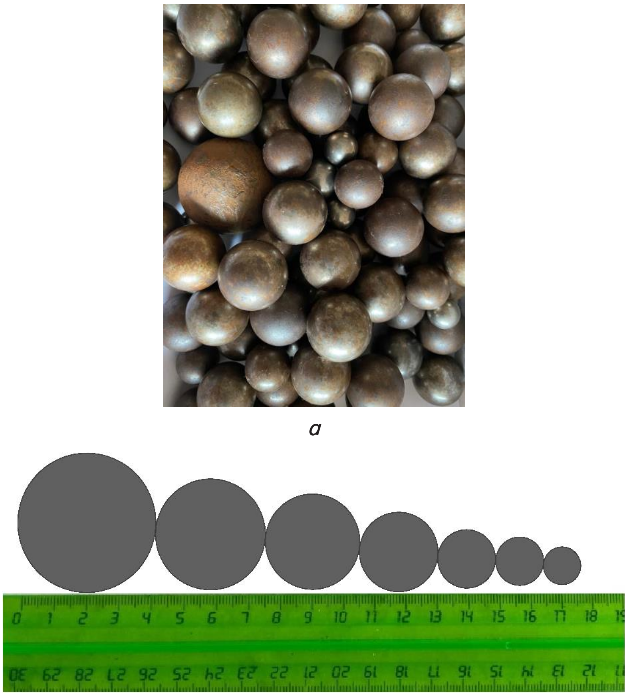


Fig. 2. Experimental setup for studying the influence of operating parameters on the efficiency of the grinding process: 1 – drum feeder; 2 – coal supply; 3 – ball drum mill; 4 – cyclone; 5 – granular filter; 6 – centrifugal fan; 7 – electric drive; 8 – control panel

The raw material from drum feeder 1 is transported into hopper 2 and through the pipe screw of the hollow trunnion of the loading, cover enters the cavity of drum 3. The drum 3, complete with covers, rotates, resting on bearings with hollow trunnions, made a single unit with the covers. The material in the cavity of drum 3 is subject to fine grinding because of the impact of the balls (Fig. 3). The type and size of these balls are shown in Table 1.



a

b

Fig. 3. Type and size of the balls used in a ball drum mill:
a – balls used during the experiment;
b – size distribution of balls

Table 1

Composition of the balls loading the mill with a standard size of 0.35×0.85

Ball weight, kg	Ball diameter, mm	Number of balls	Total ball weight, kg
0.294	40	10	2.94
0.064	25	68	4.352
0.033	20	13	0.429
0.014	15	5	0.07
Total	–	96	7.791

The filling factor of the drum volume with grinding balls is determined by eq. (1):

$$\varphi = \frac{m_t}{V \cdot \rho_g^b} = \frac{m_t}{\pi \cdot R \cdot L \cdot \rho_g^b}, \qquad (1)$$

where m_t is the total mass of balls, loaded into the drum, kg; V is the volume of the drum ball mill, m^3; ρ_g^b is the bulk density of grinding balls, kg/m^3; L is the length of the drum, m; R is the radius of the drum, m.

The total mass of balls loaded into the drum is according to [23].

To understand the grinding process taking place inside the mill, as well as to obtain numerical values of the kinematic characteristics of grinding bodies, a numerical study was performed. Numerical and experimental studies complement each other and provide high accuracy of the output data. An important aspect of a numerical experiment is the ability to visualize the calculation results. The results obtained in the course of the numerical analysis can be successfully used to optimize the performance of the on-site ball drum mills.

The experimental study will show the main technological and operational characteristics of ball drum mills affecting the efficiency of dust preparation systems. The following directions can be identified in terms of the performance of the experimental study:

– conducting experimental research, obtaining experimental data necessary for mathematical modeling;
– determination of factors affecting the efficiency of the mill;
– selection of evaluation criteria characterizing the efficiency of the grinding process;
– performing a multifactorial experimental study with the accepted range of variation of the considered parameters of the grinding process;
– determination of performance indicators of the ball mill.

The study of the processes occurring during grinding in a ball drum mill was carried out in two stages.

Stage 1. The analysis of the performance indicators of the ball mill at the TPP-2 of JSC «AMT» is made in order to determine the quantitative effect of various factors on the performance indicators of the BDM: the load factor of the grinding chamber with grinding bodies; the rotational speed of the mill drum; weighted average ball diameter.

Stage 2. Experimental studies were carried out on grinding coals in a ball mill, in order to determine the impact of the following factors on the mill performance: the rotational speed of the mill drum; weighted average diameter of the ball; the coefficient of loading the grinding chamber with grinding bodies.

To assess the grinding efficiency, a standard technique was used based on the sieve method for determining the particle size distribution [18, 24]. The laboratory installation for determining the particle size distribution of coal dust includes a «Vibrating screen AS200» screening machine from RETSCH (Germany), electronic scales, and auxiliary equipment.

The study of the grain size composition and the separation of particles into classes in laboratory conditions was carried out using a «MicroSizer 201» laser analyzer [26] (Fig. 4). With the specified equipment, it is possible to classify the coal dust grains in the range from 0.2 up to 1 000 microns. The outputs represent the relation of the weight fraction of particles to their diameter in the form of histograms and tables.

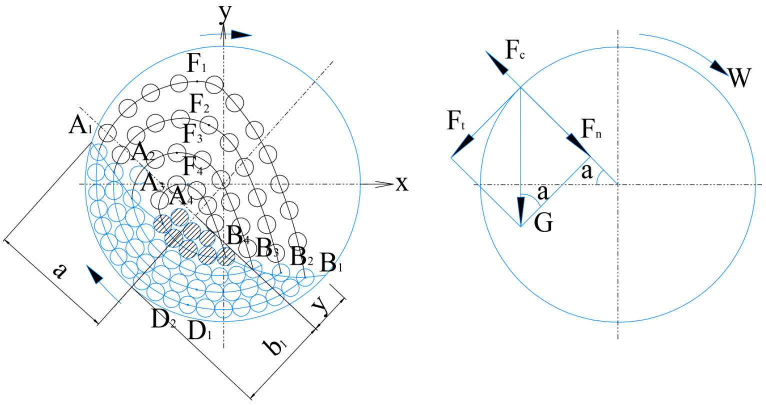
During the experimental study, the process of grinding fuel in the ball drum mill was improved in the following way: the volume of the drum of the ball mill was loaded by 20 % with a standard set of grinding bodies (steel balls) simultaneously with the fuel to be ground. The mass of the crushed fuel should be up from 14 to 18 % of the total mass of the grinding bodies. The standard set of grinding bodies (balls) used in the experimental mill is presented in Table 1. The total ball number is 96 pieces, made of low-alloy carbon steel (8HF). The mass of the ball loading is 7.791 kg.

To ensure the optimal intensity of the grinding process, the mass of additional grinding bodies should be between 30 and 35 % of the mass of a standard set of grinding bodies [27], i.e. in this case, these are small balls with a diameter of 15 mm and a mass of 0.06 kg. The filling factor of the drum volume with balls or the degree of loading in the current experiments had the following values: φ=0.14; 0.27; 0.31; 0.33; 0.35; 0.41; 0.55; and 0.68.

Fig. 4. Microsizer 201 laser analyzer for the analysis of particles of powder materials

During the grinding process, the fuel, together with additional grinding bodies, moves along the mill drum, passing the distance from the inlet neck to the outlet grate, after which the finished grinding product is discharged from the mill together with additional grinding balls. The described improvement of the grinding process in ball drum mills makes it possible to increase the efficiency of the grinding process in a ball drum mill by increasing the uniformity of the fractional composition, due to the use of grinding bodies of various sizes [28–30].

The mathematical modeling of the motion of a ball in a waterfall mill operation mode was described in detail in [31]. In a waterfall mode of operation of a ball mill, the balls, together with the fuel, can make a circular motion caused by the gravity force (Fig. 5).



a *b*

Fig. 5. Distribution of balls in the mill: *a* – waterfall mode; *b* – resulting forces

With a uniform spherical loading, a layer of fuel and balls forms a layer-by-layer ordered system consisting of «*k*» layers. The number of layers can be determined by the following relationship [29]:

$$k = \frac{b_1}{2r}, \tag{2}$$

where b_1 is the parameter of the semi-axis of the elliptical trajectory; r is the weighted average radius of the grinding load ball, m;

The efficiency of the grinding process in a ball drum mill [32, 33] by increasing the uniformity of the fractional composition is confirmed by the theory of the mechanism of material destruction in a waterfall mode of the mill charge motion. According to this theory, the amount of energy transferred to the material because of the action of the force F_1, for a specific «k_i» layer of the ball charge φ is determined by the ratio [22, 30, 31]:

$$Q_i = F_i \cdot h_i, \tag{3}$$

where Q is the productivity of the mill, kg/h; F is the force, N; h is the maximum distance covered by the force, m.

The average size of spherical fuel particles formed as a result of destruction of the volumes of deformation zones V_{0i} and $V_{0(i-1)}$, and inlet coal particles located between $(i-1)$ and i layers of the ball charging the mill drum [31] in terms of the cascade mode of motion, and in the case of loading the considered volumes by the value of the optimal load (P_{opt}), is presented with the following relation:

$$d_i = 5.05\sqrt{\frac{\left(\sqrt{2}\right)-1}{\pi} \cdot \frac{\mu(1-2\mu)}{2-\mu}} \times$$
$$\times \left[\frac{4\pi}{3\sigma_o} \cdot \sqrt{1+f} \cdot r^3 \times \times \rho_f \cdot \omega^2 r^3 \cdot \sum_{j=1}^{i} k_j \left(1 + 0.0331 \cdot \frac{\rho_f}{\rho_b}\left(1 - \frac{1}{k_j}\right)^{1/2}\right)\right], \tag{4}$$

where μ is the Poisson's ratio (values between 0.14 and 0.16 are accepted for coals); r is the weighted average radius of the grinding load ball, m; ρ_b and ρ_f are the balls and fuels density, kg/m^3; ω is the rational speed of the drum ball mill, s^{-1}; f is the friction coefficient for fuel and balls (the values for coals range from 0.3 up to 0.35).

The close look at eq. (4) shows that the dependence between d_i and ω is linear.

The same approach is used to determine the diameter of d_{i-1} $(i-1)$ particle layer of the ball charge, and also assess the average diameter (d_{avg}). The following assessment is made [34]:

$$d_{avg} = \frac{d_i + d_{i-1}}{2}. \tag{5}$$

(5) shows also that the average diameter is in a linear relation with the rotational speed of the ball drum mill. For each specific k layer, there is a specific diameter d_i, and also a resulting force, which determines the exact amount of energy transferred through the layer.

5. Results of experimental and numerical studies on the efficiency of the ball drum mill

5. 1. Determination of the significant parameters affecting the efficiency of the ball drum mill

Four parameters affecting the operation of the ball drum mill have been identified – rotational speed of the mill, degree of filling of the drum with balls, average diameter of the balls, and velocity of the supplied air.

Fig. 6 is a representation of the change of average diameter of the dust ($d_{avg,d}$) in terms of drum rotational speed (ω). The relations are obtained by the calculations of the average particle size (5) due to the performed experimental study.

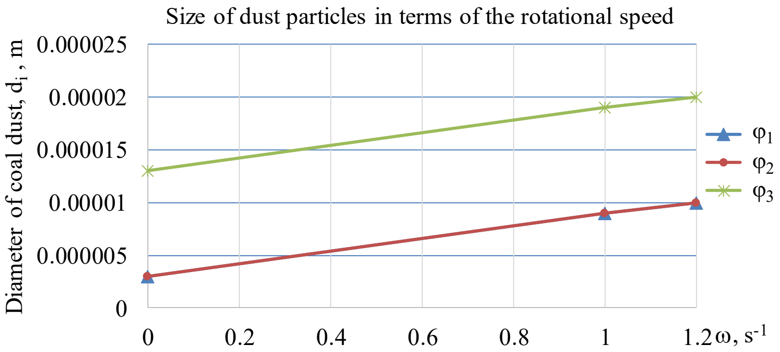


Fig. 6. Average particle size of coal dust in terms of the rotational speed of the ball drum mill at $R=0.15$ m, $f=0.3$, $r=0.027$ m, $\rho_d=2100$ kg/m^3, $\rho_b=4850$ kg/m^3, $\varphi_1=0.31$, $\varphi_2=0.33$, $\varphi_3=0.35$

Fig. 6 shows that the increase of the rotational speed of the ball drum mill increases the average size of dust particles. Statgraphics 19 software is used to perform the analysis. For each of the three regression lines, three statistic values such as t-statistics, p-value, and R-squared are presented. The analysis shows that R-squared is approximately 99 %, t-statistic is more than 3, and p-value is close to 0. The correlation coefficient is approximately 99 %. All statistical values are strong, therefore the standard error is approximately zero. Line d_1 is a regression line of d_1 vs. ω. The equation of the fitted model is:

$$d_1 = 0.00301613 + 0.0058871 \cdot \omega. \tag{6}$$

Since the P-value in the ANOVA table is less than 0.05, there is a statistically significant relationship between d_1 and ω, s^{-1} at the 95.0 % confidence level. The R-squared statistic indicates that the model as fitted explains 99.9437 % of the variability in d_1. The correlation coefficient equals 0.999719, indicating a relatively strong relationship between the variables. The standard error of the estimate shows the standard deviation of the residuals to be 0.000127. This value can be used to construct prediction limits for new observations by selecting the Forecasts option from the text menu. The mean absolute error (MAE) of 0.0000645161 is the average value of the residuals. The Durbin-Watson (DW) statistic tests the residuals to determine if there is any significant correlation based on the order in which they occur in your data file. Line d_2 is a regression line of d_2 vs. ω. The equation of the fitted model is:

$$d_2 = 0.00301613 + 0.0058871 \cdot \omega. \tag{7}$$

Since the P-value in the ANOVA table is less than 0.05, there is a statistically significant relationship between d_2 and ω, s^{-1} at the 95.0 % confidence level. The R-squared statistic indicates that the model as fitted explains 99.9437 % of the variability in d_2. The correlation coefficient equals 0.999719, indicating a relatively strong relationship between the variables. The standard error of the estimate shows the standard deviation of the residuals to be 0.000127. The mean absolute error (MAE) of 0.0000645161 is the average value of the residuals. The Durbin-Watson (DW) statistic tests the residuals to determine if there is any significant correlation based on the order in which they occur in the data file. Line d_3 is a regression line of d_3 vs. ω. The equation of the fitted model is:

$$d_3 = 0.0130161 + 0.0058871 \cdot \omega.$$

The same conclusion can be made for this model. The correlation coefficient equals 0.999719, indicating a relatively strong relationship between the variables.

The standard error of the estimate shows the standard deviation of the residuals to be 0.000127. The mean absolute error (MAE) of 0.0000645161 is the average value of the residuals.

The relation is linear for each specific value of the drum load factor. For example, at the rotational speed of the mill drum $\omega=0.89$ s^{-1}, the average particle size of the final product is $d_i=0.00852$ mm. With an increase in the rotational speed of the drum mill to $\omega=1.2$ s^{-1}, the average diameter increases to $d_i=0.019$ mm.

At $\varphi=0.35$ and the rotational speed of the mill drum $\omega=0.98$ s^{-1}, the average particle size of the final product increases to $d_i=0.019$ mm. Further increase in the rotational speed of the mill drum to $\omega=1.2$ s^{-1} leads to an increase in the diameter to $d_i=0.020$ mm.

On the other hand, at each fixed value of the rotational speed, when the load factor increases, the average particle size of coal dust increases nonlinearly, and apparently, at the load factor $\varphi\to1$, the average size of dust particles tends to the particle size of the initial fuel material. Loading the mill with coals during the operation of a ball mill is also of great importance. With a small amount of coal, the number of idle blows of the balls increases. With a large amount, the impact force is softened by a layer of coal of increased thickness. Fig. 7 shows the relations of the experimental ball drum mill at different loading levels with grinding balls ($\varphi=14$, 27, 41, 55 and 68 %) and the amount of the initial fuel. The highest productivity was obtained with a load of balls $\varphi=41$ % and a weight load of the mill with coal of 1500 g, equal to 187 g/h.

The results provided in Fig. 7 were obtained through the experimental setup of the ball drum mill, where the maximum fuel load is 2800 g. The purpose of the experiments was to determine the degree of ball loading ensuring maximum productivity.

The same statistical analysis in terms of Fig. 6 was performed. For all the dependent variables (14, 27, 41, 55 and 68 %), the regression lines were prepared:

$$\begin{aligned} 14\,\% &= \exp(4.59405 - 0.000612054 \cdot \text{weight load}),\\ 27\,\% &= \exp(4.96614 - 0.000131081 \cdot \text{weight load}),\\ 41\,\% &= \exp(5.20927 - 0.000161295 \cdot \text{weight load}),\\ 55\,\% &= \exp(4.43554 - 0.000199994 \cdot \text{weight load}),\\ 68\,\% &= \exp(5.05189 - 0.000140285 \cdot \text{weight load}). \end{aligned} \tag{8}$$

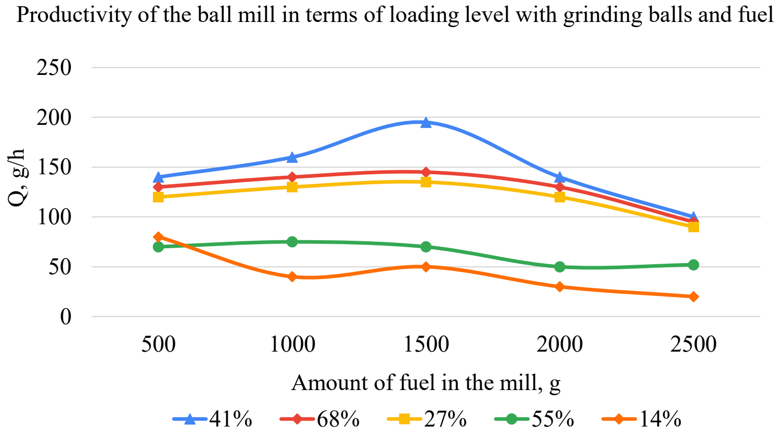


Fig. 7. Relation of productivity of the ball mill in terms of loading level with grinding balls and fuel

With the degree of loading the drum volume with steel balls by 41 % (consisting of various balls with diameters of 15, 20, 25, and 40 mm) and fuel by 59 %, the mill productivity increases from 50 g/h to 187 g/h, i.e. almost 3.74 times. This is a prove not for a stable mode, but the intense nature of the dependence of the productivity (Q) and the degree of loading the mill with grinding balls and fuel.

An open-cycle operating ball mill is used during the experimental study in order to determine the following main factors affecting the performance of the mill:

– rotational speed of the ball drum mill;
– weighted average diameter of the ball;
– velocity of the supplied air;
– coefficient of loading the grinding chamber with grinding bodies [21].

During a ball charging process, industrial balls are used, the technical specification of which is provided in Table 1. The qualitative characteristics of coal dust have been determined:

– fineness of grinding $R_{90\,\%}$;
– productivity of the mill Q, kg/h;
– power consumed by the mill P, W;
– specific surface area of the final product S, cm^2/g.

The fineness of grinding and specific surface area of the final product were determined by the method of sieve analysis by sieving a sample of coal dust [35] using vibrating screens of various diameters 1 000, 500, 200, 90, 71 µm.

The mill operating mode is characterized by grinding time and drum rotational speed.

The milling product itself, all other things being equal, is characterized by its specific surface (S), largest size (d_{out}), and in some cases, by its grain size composition (granulometric characteristics $R_{90\,\%}$) [15]. Granulometric distribution is presented in Fig. 8.

On the left vertical axis, the total output R_x is presented, on the horizontal axis – the values of the lower size limits of particles, in microns. Specific power consumption for fuel grinding is associated with many factors, such as changes in the grindability coefficient kg of fuel, fineness of grinding dust R_{90}, mill productivity, drying agent feed rate, drying agent temperature and ball diameter [19, 20, 31].

5. 2. Analyzing significant parameters and performing a multifactorial experiment

The results of the experiment study have been used to prepare the factorial experiment [36]. Table 2 shows the averaged results from the experimental study that allows compiling a design matrix for a full-factor experiment. In terms of the results from Table 2 and their statistical processing using commercial software, regression equations in the form of $Q=Q(x_1, x_2, x_3, x_4)$, $P=P(x_1, x_2, x_3, x_4)$, and $S=S(x_1, x_2, x_3, x_4)$ are obtained. The regression equation obtained [37] shows the behavior of the technological, energy, and economic indicators such as Q – mill productivity, P – power consumed by the mill, and S – specific surface area of the final product. The regression equation is valid only in a narrow range of variation of the processed parameters.

The regression equation (9) is derived based on the data obtained in accordance with 24 on-site trials (experimental tests) [35]:

$$y = b_o + \sum_{i=1}^{n} b_i x_i + \sum_{\substack{i=1 \\ j\neq 1}}^{n} b_{ij} x_i x_j + \sum_{i=1}^{n} b_{ii} x_i^2. \qquad (9)$$

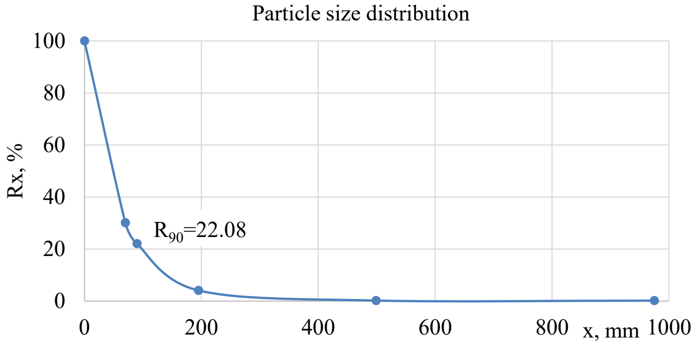


Fig. 8. Grain characteristics of Karaganda coal dust

Table 2

Summarized results from the numerical study

No.	Matrix						
	x_1	x_2	x_3	x_4	Q, kg/h	P, W	S, m^2
	ω	d_{avg}	v	φ			
1	2	3	4	5	6	7	8
1	+1	+1	+1	+1	66.8	1162	2396
2	–1	+1	+1	+1	64.2	1198	2469
3	+1	–1	+1	+1	69.8	1240	2310
4	+1	–1	+1	+1	65.2	1169	2390
5	+1	+1	–1	+1	67.9	1210	2326
6	–1	+1	–1	+1	68.1	1215	2398
7	+1	–1	–1	+1	74.7	1220	2318
8	–1	–1	–1	+1	66.1	1133	2368
9	+1	+1	+1	–1	68.2	1220	2276
10	–1	+1	+1	–1	63.3	1190	2373
11	+1	+1	+1	–1	73.3	1183	2293
12	–1	–1	+1	–1	67.7	1185	2252
13	+1	–1	–1	–1	71.9	1210	2301
14	–1	+1	–1	–1	65.1	1153	2357
15	+1	–1	–1	–1	70.1	1198	2304
16	–1	–1	–1	–1	69.5	1161	2345
17	1.414	0	0	0	68.7	1202	2320
18	–1.414	0	0	0	66.6	1165	2420
19	0	1.414	0	0	66.2	1220	2450
20	0	–1.414	0	0	68.9	1180	2285
21	0	0	1.414	0	66.1	1199	2441
22	0	0	–1.414	0	68.8	1185	2300
23	0	0	0	1.414	66.1	1240	2480
24	0	0	0	–1.414	68.9	1169	2251
25	0	0	0	0	68.2	1198	2371

Equation (9) gives valuable information about the main parameters affecting the grinding process. The productivity, power consumed and surface area can be independently adjusted to have the optimal operation of the drum mill.

5. 3. Obtaining regression equations for the significant parameters affecting the operation of the ball drum mill

The significance of the regression coefficients of the relations obtained was determined by calculating the Student's criterion [30]. Validation of the regression model for adequacy was performed by calculating the Fisher criteria, which reflects how well this model explains the total variance of the dependent variable, and compares with the table values.

The regression equation characterizing the relation of the mill productivity Q in terms of the factors x_1, x_2, x_3, x_4 in coded form is expressed with:

$$\begin{aligned}Q=&67.34+1.83x_1-1.241x_2-0.93x_3-0.52x_4+\\&+0.270018x_1^2+0.22x_2^2+0.17x_3^2+0.19x_4^2-\\&-0.33x_1x_2+0.1125x_1x_3-0.14x_1x_4-0.38x_2x_3+\\&+0.2x_2x_4-0.41x_3x_4.\end{aligned} \quad (10)$$

With some transformations, taking into account the levels of variation of the main factors, the following regression equation describing the grinding process is as follows:

$$\begin{aligned}Q=&354.62-176.29\omega-2.19d_{avg}+100.89\cdot\upsilon-\\&-1{,}401.08\varphi+75\omega^2+0.22d_{avg}^2+17\upsilon^2+1{,}940\varphi^2-\\&-5.42\omega d_{avg}+18.67\omega\,\upsilon+228.33\omega\varphi-\\&-3.75d_{avg}\upsilon+20d_{avg}\varphi-412\upsilon\varphi.\end{aligned} \quad (11)$$

Some main conclusions can be made based on the performed regression analysis: factor x_1, the relative rotational speed of the mill drum has the greatest impact on the positive change in mill productivity. The coefficients at x_1 and x_1^2 are both positive and have the highest specific impact on the mill productivity. When the relative rotational speed of the drum mill increases, the productivity also increases. This is due to the fact that the balls and material are centrifuged at high relative rotational speeds of the drum, as a result, the finished product decreases and becomes coarse. Then coefficients x_2, x_3, and x_4 are negative. At x_2 (weighted average diameter of the ball), x_3 (speed of the supplied air in the mill drum), and x_4 (load factor of the grinding media), the overall productivity of the mill decreases [21].

The regression equation presenting the relation of the power consumed by the mill in terms of the factors obtained in the current study has the following explicit form:

$$\begin{aligned}P=&10{,}965.62+2{,}950.29\omega-209{,}000d_{avg}+\\&+214.06\upsilon-48{,}361.37\varphi-163{,}269\omega^2+\\&+2{,}380{,}000d_{avg}^2-162.55\upsilon^2+46{,}276\varphi^2-\\&-69{,}791.67\omega d_{avg}-343.75\omega\upsilon+7{,}812.5\omega\varphi-\\&-1{,}875d_{avg}\upsilon+356{,}000\cdot d_{avg}\varphi+937.5\upsilon\varphi.\end{aligned} \quad (12)$$

A similar equation can be proposed for the specific surface area:

$$\begin{aligned}S=&116.39+634{,}433\omega-274{,}000d_{avg}-4{,}671.3\upsilon+\\&+255{,}669\varphi-055.56\omega^2-860{,}000d_{avg}^2-715\upsilon^2-\\&-96{,}500\varphi^2-70{,}833.33\omega d_{avg}-938\omega\upsilon-2{,}300\omega\varphi+\\&+76{,}300d_{avg}\upsilon++1{,}190{,}000d_{avg}\varphi+10{,}500\upsilon\varphi.\end{aligned} \quad (13)$$

The distribution of the response functions from the relative rotational speed of the mill drum is presented in Fig. 9.

The obtained regression equations (10)–(13) allow optimizing the grinding process. With the proper value selection of the input parameters (ω, φ, v, d_{avg}), it is possible to adjust the process running most efficiently.

When increasing the relative rotational speed of the drum mill from 0.76 to 0.92 (increasing the total mill power by 17.9 %), the energy consumption increases from 1170 W to 1225 W or by 4.5 %. At the same time, the production capacity of the mill increases from 65 kg/h to 72 kg/h, i.e. by 9.7 %, and the specific surface area of the final product decreases from 2 439 cm^2/g to 2 238 cm^2/g, which is 8.2 % less.

Fig. 9 shows that the largest specific surface area of the final product and low power consumed by the mill drive are achieved at a relative rotational speed of the mill drum amounted to ω=0.76. In this case, the productivity of the mill has a minimum value, therefore, this option is preferable in the case where the finest final product is required.

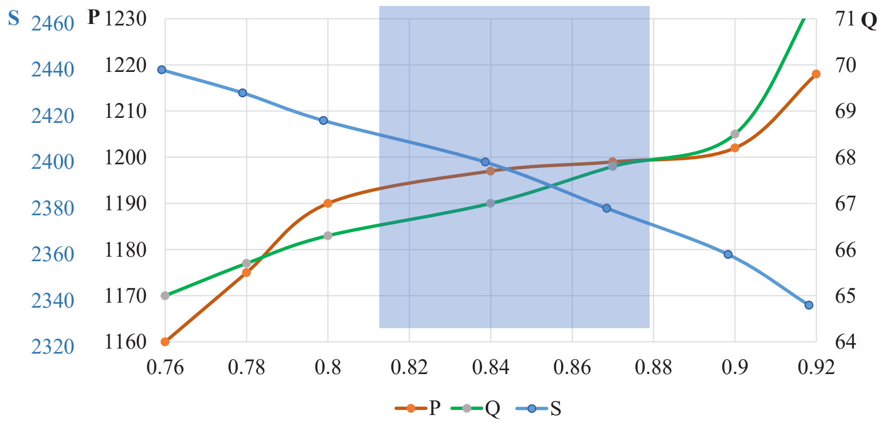


Fig. 9. Curves of mill productivity, power consumed, specific surface of coal dust in terms of the relative rotational speed of the ball drum mill

If, however, high requirements are not imposed on the quality of the final product and it is necessary to increase the productivity of the mill, then increasing the relative rotational speed of the mill drum is recommended. In this case, operational parameters from ω=0.81 up to 0.87 should be adopted.

Considering the values of the mill productivity, the power consumed, and the specific surface of coal dust, the weighted average diameter of the balls was determined – it should be in the range of d_{avg}=33.5 up to 34.5 mm.

For the optimal performance of the ball drum mill, the load factor of the grinding media should be φ=0.325 up to 0.335. For the velocity of air supplied, the acceptable region is v=0.2 up to 0.3 m/s.

Experimental studies of the grinding process in a ball drum mill performed by [21, 38–40] were used to support and verify the data obtained during the regression analysis.

6. Discussion of the results obtained via experimental and numerical studies

Grinding is the most important technological process in the production of coal dust. The finer the dust, the faster it burns in the furnace of the boiler unit. To obtain finely dispersed coal dust, continuous drum mills are most often used. The fineness of fuel grinding in a ball mill is determined by:

– the properties of the material to be ground, more precisely, its grindability coefficient;

– the type and design of the mill, the degree of filling of the drum volume with grinding media, as well as the characteristics of the grinding media: their configuration, material, porosity, etc.;

– the operation mode of the mill, which is characterized by the grinding time and drum speed.

Therefore, the purpose of this work is the development of a methodology for selecting a rational composition of grinding media; operation modes of the mill, ensuring the maximum efficiency of the coal grinding process, taking into account its physical and mechanical properties and the development of a mathematical model for determining the optimal parameters for the destruction of material in ball drum mills.

The main objective of this work is to study the effect of the fractional composition of the initial fuel on the efficiency of the grinding process in a ball mill [5]. The initial coal delivered to the thermal power plant passes the stage of fine crushing in a crusher, the design of which is proposed by the authors [8] and has dimensions up to 2.5 mm. The effectiveness of the dust system in the new conditions will be proved by the creation of a mathematical model of the BDM characteristics, which determine the quality of the grinding process. The ball mill mathematical model should ensure the preparation of coal dust with a grinding fineness for the initial coal R_{90}=18 up to 22 %, which is an indicator for industrial mills. The boundary condition for the mathematical modeling is that the coal dust obtained should have a size of less than 90 microns when performing a sieve analysis. Only from 18 up to 22 % of the composition of the sample taken for analysis can have dimensions of more than 90 microns. The results of the analysis of the coal dust composition with a Microsizer 201 laser analyzer confirm the accepted boundary conditions. The proof is the graph in Fig. 6, where the minimum average particle sizes reach even 25 μm to 5 μm. The minimum average particle size of coal dust depends on the nature of the movement of fuel particles in the mill, on the density of the fuel and grinding balls, and most importantly, on the relative speed of the mill drum. The graph shows the nature of the increase in the average size of dust particles with increasing drum speed and under certain conditions it reaches 90 microns.

Based on the results of the experimental study, a mathematical model was selected that shows improved characteristics of the BDM. These mill features include:

– productivity Q, kg/h;

– power consumed by the mill drive P, W;

– specific surface area of the finished product S, cm^2/g.

The mathematical model was obtained using the theory of a full-factor experiment [26]. This theory uses the central compositional rotatable plan of the full factorial experiment. Table 2 presents the averaged results of experimental studies, which made it possible to compile a plan matrix for a full-factor experiment. Based on the results of the experiments and their statistical processing using commercial software, we have obtained regression equations $Q=Q(x_1, x_2, x_3, x_4)$, $P=P(x_1, x_2, x_3, x_4)$, $S=S(x_1, x_2, x_3, x_4)$. Multifactorial analysis shows the relationship between such economic indicators as Q – mill productivity, P – power consumed by the mill, and S – specific surface of the final product in terms of ω, d_{avg}, v, φ.

In the current study, the general purpose is to optimize the operation of the BDM at the TPP-2 JSC «AMT» in Temirtau. For this purpose, preliminary experimental studies of the BDM operation were carried out and the relations between the main technological parameters of the grinding process (grinding fineness, polydispersity coefficient) and a number of indirect indicators were determined.

Currently, there are no reliable methods for finding the optimal load of the mill to achieve the maximum possible productivity, since exceeding the optimal load of the mill causes its emergency state – blockage of the mill with the material being ground. The control of the grinding process parameters shows an increased specific energy consumption with a decrease in the grinding capacity of the mill.

Based on the experimental data obtained and the numerical experiment, regression equations were obtained that describe the grinding process in its natural form. Regression equations characterize the dependence of power consumption, mill productivity and the specific surface area of the finished coal dust on the main factors that determine the operating mode of the mill installation. The obtained scientific results allow improving the production cycle of Temirtau TPP-2 to achieve the efficiency of grinding and other power plants of the Republic of Kazakhstan operating on solid fuel.

The limitations inherent in the obtained mathematical model of the characteristics of the BDM operation are that the accuracy of the model depends on the accepted levels and intervals of variation of the factors x_1, x_2, x_3, and x_4. For experiments carried out with other types of mills such as hammer, medium speed, fan, this model will not be useful, since it is necessary to set other factors x_1, x_2, x_3, and x_4, depending on their operating conditions.

Various types of mills are used for the preparation of coal dust for boilers, but the energy spent directly on the preparation of the initial coal and grinding is at least 10 % of all TPP needs. Therefore, any progress in this area can be a source of significant savings. During operation, ball drum mills have proven their reliability when grinding various materials. The wide distribution of ball mills determines the simplicity of design, high hourly productivity. However, they have significant disadvantages:

- high specific metal and energy intensity;
- low coefficient of performance (COP), less than 15 %;
- low energy intensity of the grinding process, due to the low speed of the action of grinding bodies on the crushed material – about 50 % of grinding bodies do not participate in the grinding process; the working volume of the mill is used by 35 %;
- high specific consumption of grinding media and mill lining material.

Despite the listed shortcomings, the ball drum mill remains the main grinding unit for grinding coal and other materials. The foregoing determines the relevance of solving the problem of improving the quality of finished coal dust, as well as increasing the grinding efficiency by modernizing the design of a ball mill. The future work of the team is to create a prototype mill, install a holder with holes inside the drum, which allows getting a product of the required quality, ensures the appropriate nature of the force impact on the original ground material.

7. Conclusions

1. To improve the energy efficiency of the grinding process in a ball drum mill, it is necessary to identify the significant operational parameters. Due to the performed experimental study, and collected and analyzed on-site measurements, it became clear that rotational speed of the ball drum mill, average diameters of the balls, velocity of the supplied air and degree of filling of the mill with balls are classified as the most significant parameters affecting the energy efficiency of the grinding process.

2. Multifactorial approach was applied in order to qualitatively measure the impact on the previously selected significant parameters to the economical one – Q – mill productivity, P – power consumed by the mill, and S – specific surface area. 25 different sets of trials have been made in order to show the significance of each factor, as well as the range of significance.

3. Regression analysis based on both mathematical modeling and on-site data was performed. Qualitative relations for all economic parameters were presented in terms of ω, d_{avg}, v, φ. Those relations allow analyzing the current state of the grinding process in terms of energy consumption and proposing a mechanism for improvements. In addition, via the relation, the operational region for a specific BDM operating at different size large scale TPP can be specified. For the concerned BDM, fine coal grinding could be observed when the degree of filling with balls is 0.31; 0.33; 0.35; 0.41. The specific range for the other operational parameters is also stated.

Increasing the energy efficiency of the grinding process of coals in a ball drum mill will reduce the price of the final energy. Using the proposed regression model will provide the user with a tool to examine the current state of energy consumption by the drum mill, and to make a suggestion for improvements. The results can be extrapolated for different scales of TPP with the same grinding equipment.

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References

1. Kazhumukhanova, M. Z. (2015). Trace elements in coal deposits of Kazakhstan. Problems of geology and subsoil development: proceedings of the XIX Problems of Geology and Subsurface Development: Proceedings of the 19th International Scientific Symposium of students, Postgraduates and young Scientists devoted to the 60th Anniversary Soviet People' s Victory against fascism in the Great Patriotic War 191-1945 years. Pat I; Tomsk Polytechnic University. Tomsk: TPU Publishing House, 105–106. Available at: https://portal.tpu.ru/files/conferences/usovma/2015/vol1_2015.pdf
2. Roslyakov, P. V., Stepanova, A. N., Sivakovsky, A. M. (2018). Development of an algorithm for the optimal selection of the best available technologies at TPPs. Modern trends in environmentally sustainable development: International scientific conference dedicated to the memory of academician T. S. Khachaturov. Moscow: Faculty of Economics, Moscow State University, M. V. Lomonosov, 142–143. Available at: https://www.econ.msu.ru/sys/raw.php?o=51223&p=attachment

3. Mingalieva, A. S., Zatsarinnaya, Y. N., Vatchagina, E. K. (2005). Analysis of the operation of the fuel preparation system of the pulverized coal TPP. Energy problems, 1-2, 22–31. Available at: https://cyberleninka.ru/article/n/analiz-raboty-sistemy-podgotovki-topliva-pyleugolnoy-tes
4. Huang, P., Miao, Q., Ding, Y., Sang, G., Jia, M. (2021). Research on surface segregation and overall segregation of particles in a rotating drum based on stacked image. Powder Technology, 382, 162–172. doi: https://doi.org/10.1016/j.powtec.2020.12.063
5. Huang, P., Miao, Q., Sang, G., Zhou, Y., Jia, M. (2021). Research on quantitative method of particle segregation based on axial center nearest neighbor index. Minerals Engineering, 161, 106716. doi: https://doi.org/10.1016/j.mineng.2020.106716
6. Ivanov, S. D., Kudryashov, A. N., Oshchepkov, V. V. (2021). Determining Optimum Productivity of a Ball Drum Mill When Milling Brown Coals. Thermal Engineering, 68 (2), 136–141. doi: https://doi.org/10.1134/s0040601521010134
7. Machado, M. V. C., Santos, D. A., Barrozo, M. A. S., Duarte, C. R. (2017). Experimental and Numerical Study of Grinding Media Flow in a Ball Mill. Chemical Engineering & Technology, 40 (10), 1835–1843. doi: https://doi.org/10.1002/ceat.201600508
8. Golyshev, L. V., Mysak, I. S. (2012). The method for determining the ball load and the grinding capacity of a ball-tube mill from the power consumed by its electric motor. Thermal Engineering, 59 (8), 589–592. doi: https://doi.org/10.1134/s0040601512080058
9. Huang, P., Ding, Y., Wu, L., Fu, S., Jia, M. (2019). A novel approach of evaluating crushing energy in ball mills using regional total energy. Powder Technology, 355, 289–299. doi: https://doi.org/10.1016/j.powtec.2019.07.050
10. Naumova, M. G., Morozova, I. G., Aliev, K. B. (2020). Creating a project for modernizing the feeding balls device to a ball mill using 3D modeling. IOP Conference Series: Materials Science and Engineering, 971 (5), 052025. doi: https://doi.org/10.1088/1757-899x/971/5/052025
11. Romanovich, A., Osalou, A., Mamatova, V., Pahomov, E. (2019). The grinding bodies movement dynamics study in a ball mill equipped with energy-exchanging devices. IOP Conference Series: Materials Science and Engineering, 698 (6), 066037. doi: https://doi.org/10.1088/1757-899x/698/6/066037
12. Stoimenov, N., Karastoyanov, D., Klochkov, L. (2018). Study of the factors increasing the quality and productivity of drum, rod and ball mills. AIP Conference Proceedings 2022, 020024. doi: https://doi.org/10.1063/1.5060704
13. Nazmeev, Yu. G., Mingaleeva, G. R. (2005). Fuel supply and dust preparation systems for TPPs. Moscow: Publishing house of MEI, 479.
14. Sidelkovsky, P. N., Yurenev, V. N. (1988). Boiler plants of industrial enterprises. Moscow: Energoatomizdat, 528.
15. Levit, G. T. (1990). Dust preparation at thermal power plants. Moscow: Energoatomizdat, 384.
16. Industrial technical instruction (PTI) 102-47-11. ArcelorMittal Temirtau JSC CHP-2. Production and technological instruction for the operation of the dust preparation system with ball mills of the type BDM-320/570. Temirtau, 19.
17. Pletnev, G. P. (2016). Automation of technological processes and production in heat power engineering. Moscow: MPEI, 352.
18. Kamarova, S., Abildinova, S., Terziev, A., Elemanova, A. (2020). The efficiency analysis of the SH-25A ball drum mill when grinding industrial products of fossil fuels. E3S Web of Conferences, 180, 01003. doi: https://doi.org/10.1051/e3sconf/202018001003
19. Isaev, V., Kamarova, S. N. (2019). Pat. RK No. 5046. Coal crushing device. No. 2019/1145.2; declareted: 25.12.2019, published: 12.06.2020.
20. Pellet Feed Grinding Process Optimization Through Simulation Tools And Mathematical Modeling (2015). Rio de Janeiro, 189. Available at: https://www.metalmat.ufrj.br/index.php/br/pesquisa/producao-academica/dissertacoes/2015-2/285-pellet-feed-grinding-process-optimization-through-simulation-tools-and-mathematical-modeling/file
21. Shuvalov, S. I., Novoseltseva, S. S., Verenin, A. A., Voroshilov, O. A. (2017). Mathematical model of a dust-system with a ball-type drum mill for the analysis of classification schemes. Bulletin of ISEU, 5, 10–18. doi: https://doi.org/10.17588/2072-2672.2017.5.010-018
22. Mikheev, P. G. (2005). Mathematical modeling of the motion of coal particles in a ball mill drum. Abstracts reports Int. scientific and technical conf.: State and prospects for the development of electrical technology (XII Benardos readings). Ivanovo: ISEU, 167.
23. Kamarova, S. N., Abildinova, S. K. (2019). Optimization of electricity consumption for dust preparation in ball-drum mills Sh-25A at TPP-2 of ArcelorMittal Temirtau JSC. Energy management, quality and efficiency of energy use: Proceedings of the IX International Scientific and Technical Conference. Blagoveshchensk, 370–377.
24. GOST 2093-82. Solid fuel. Size analysis. Available at: https://docs.cntd.ru/document/1200024037
25. Laser particle analyzers «Microsizer» model 201A and 201C. Operation manual C 201.001. RE (2008). Saint Petersburg.
26. Sokolov, N. V. Kiselgof, M. L. et. al. (1971). Calculation and design of dust preparation plants of boiler units (Normative materials). Leningrad: NPO CKTI; VTI, 312.
27. Lebedev, A. N. (1969). Preparation and grinding of fuel at power plants. Moscow: Energiya, 520.Andreev, A. A. (2009). About the model of the grinding process in a ball drum mill. Processing of ores, 4, 3–7.
28. Zhukov, V. P. (1987). Optimal size distribution of grinding bodies in drum mills. Intensification of mechanical processing of bulk materials. Ivanovo, 40–43.
29. Petrov, A. V. (2015). Modeling of processes and systems. Saint Petersburg: Lan, 288. Available at: https://e.lanbook.com/book/68472

30. Kamarova, S. N. (2020). Study of the thermodynamic efficiency of solid fuel preparation systems at ArcelorMittal Temirtau JSC. Energy and energy saving: theory and practice. Collection of materials v All-Russian scientific and practical conference. Kemerovo. Available at: https://www.elibrary.ru/item.asp?id=45771865
31. Bogdanov, V. S. (1990). Calculation of energy parameters of interaction of grinding bodies in ball drum mills. Cement, 12, 18–22.
32. Abildinova, S. K., Kamarova, S. N. (2019). Optimization of electricity costs power of schemes of preparation of coal dust of B-25A ball drum mill of CHPP-2 JS of «ArselorMittalTemirtau». Proceedings of the IX International Scientific and Technical Conference. Energy: management, quality and efficiency of energy use. Blagoveshchensk: Amur state. un-t, 370–376. Available at: https://www.amursu.ru/upload/files/education/enf/konf/sbornik.pdf
33. Zhukov, V. P. (1991). Experimental study of the influence of the surface of grinding bodies on the grinding rate. Izv. University, Chemistry and chemical technology, 34 (11), 110–111.
34. Zhukov, N. P., Chekh, A. S. et. al. (2007). Determination of particle size distribution of solid fuels by the sieve method. Tambov: Izd-vo Tamb. state tech, 12. Available at: http://window.edu.ru/resource/816/64816/files/jukov-l.pdf
35. Antony, J. (2014). Design of experiments for Engineers and Scientist. Elsevier. doi: https://doi.org/10.1016/C2012-0-03558-2
36. Balakhtina, E. E. et. al. (2005). Study of the motion of balls in the grinding chamber of a drum mill using numerical modeling. Announcemnts University of Mining Journal, 12, 198–204. Available at: https://giab-online.ru/files/Data/2005/12/7_Balahnina15.pdf
37. Krykhtin, G. S., Kuznetsov, L. N. (1993). Intensification of the work of mills. Novosibirsk: VO «Science», Siberian Publishing Company, 240. Available at: https://ru.ua1lib.org/book/3254139/d33877
38. Zheng, Y., Kuznetsova, M. M., Ved', V. E., Aleksina, A. A. (2016). Experimental studies of the energetically effective conditions of grinding of solids. Technical Physics, 61 (5), 703–706. doi: https://doi.org/10.1134/s1063784216050273
39. Dmitrak, Yu. V. (2003). Features of the motion of the grinding charge in a ball drum mill. Mining Journal, 2, 54–57.