ANALYTICAL STUDY OF THE ENERGY CONSUMPTION OF DRUM MILLS ACCORDING TO THEIR SIZE

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ABSTRACT. In the design of processing factories, the main problem is the choice of the sizes of the drum mills. The factors influencing the choice of a mill are several, each meeting different requirements. One of the main ones is the possibility to supply the technological scheme with a minimum number of mills. This leads to the choice of large-scale machines with the highest price and repair costs. The result of such a choice can be the unnecessary high cost of the milling process. Therefore, the second factor in the choice is the energy consumption of each machine per tonne of processed ore. Various types of drum ball mills were investigated in the paper and their energy consumption was calculated under the same conditions according to the known methodologies. An automatic calculation programme was developed according to the shown methodology. Based on the results obtained, some conclusions are drawn.

Keywords: ball mill, energy consumption, size, power of engine, relative power consumption

АНАЛИТИЧНО ИЗСЛЕДВАНЕ НА ЕНЕРГОРАЗХОДА НА БАРАБАННИ ТОПКОВИ МЕЛНИЦИ СПОРЕД ТИПОРАЗМЕРА ИМ

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РЕЗЮМЕ. При проектиране на обогатителни фабрики основен проблем е изборът на типоразмери на барабанните мелници. Факторите, влияещи на избора на мелница са няколко, като всеки от тях удовлетворява различни изисквания. Един от основните е възможността за удовлетворяване на технологичната схема е с минимален брой мелници. Това води до избора на едрогабаритни машини с най-висока цена и разходи за ремонт. Резултатът от такъв избор може да е излишно оскъпяване на процеса смилане. Затова втори фактор при избора е енергоразходът на всяка машина за тон преработена руда. В статията са изследвани различни типоразмери барабанни топкови мелници, изчислен е техният енергоразход при еднакви условия според известна методика. Разработена е програма за автоматично изчисление, според показаната методика, и въз основа на получените резултати са направени съответните изводи.

Ключови думи: топкова мелница, мощност на двигател, енергоразход, размер, специфичен енергоразход

Introduction

According to the Sustainable Development Paradigm, social, economic and environmental issues are accepted to be considered in a complex way in every human and productive activity. In recent years, manufacturers have become aware of the relationship between production operations, the quality of the environment and the welfare and health of employees (Rosen, Kishawy, 2012). Naturally, the sustainability criteria apply to the different stages of existence of industrial sites - designing, renovating, building, operations. The achievement of these complex objectives is also important in the mining and processing sector, which puts producers and engineers in front of four key environmental objectives: 1) Human extinction, 2) Sustainable development, 3) Conservation of biodiversity, 4) Aesthetic wealth [A. Szekeres, 2016]. In this aspect, the impact assessment of the mining and processing sector is best considered not only for the entire life cycle but also for the full range of activities involving the product (ERP), process (ERP), facility (ERF), service (ERS) and infrastructure (ERI). Due to the need to meet the sustainability criteria under changed requirements, standards, regulations and laws, it is often necessary to change technological lines or to build new enterprises.

Relative power consumption for technological processes

The factor of relative power consumption as part of the objectives for achieving sustainable development in the choice of mills for the mining sector is considered in the article. In the life cycle of production, this is one of the most energy-intensive processes not only for the mining sector, but also for other economic activities. From the reference of literature sources it has been found that mills in the light industry and in particular in the food industry have relatively high energy consumption in the production cycle. Rice mill engines consume between 80 and 85% of total energy in the life cycle from flaking to packing rice (Pachanawan, 2017). Similar are the statistics data for other sectors of the food industry like sugar cane production, where mainly roll crusher or roller mills are used (Ștefan, Voicu, 2013).

For the mining sector, 50% of the electricity consumed was found to be the crushing and milling process in the full production cycle of the four parts of the chain: exploration, extraction, processing and recycling (Jeswiet, 2016). It is estimated that approximately 60% of this energy is consumed in the milling process. The data from foreign sources overlap with those for Bulgarian mining enterprises, where 60% of the consumption is of synchronous engines (SM) driving the mills, and 40% is from asynchronous engines in the crushing process (Kurtzelin et al., 2009). Under the sustainability criteria, scientists are analysing these issues not only in order to save both the electrical energy and resources. The reason is that the quality of the product at the output of a particular process has an effect on the quality and consumption of energy and raw materials in the next one.

Energy saving approaches can be either theoretical or experimental, performed by machine operators. The latter are very expensive and usually do not lead to optimal results (Jafarzadeh, Khodaygan, 2019). To achieve synergy, it is necessary to reduce the energy consumption while preserving the quality of the resulting product, for which optimisation of the processing parameters is necessary. Research has recently been done to achieve targeted features such as maximising tool life, maximising material removal rate (MRR), maximising surface quality of grain size while minimising energy consumption or material consumption, compensating for energy losses in propulsion synchronous motors through change of supply voltage (Kurtzelin et al., 2009), determination of vibrations at maximum MRR and others (Jafarzadeh et al., 2019). Various methods, algorithms, mathematical apparatus (Mryankov, 2007), machine algorithm for calculation, neural networks, etc. are used to achieve the optimal parameters of the surveyed objects. In order to achieve the target function, it is good to compare several methods and select the one with the smallest error (Singh Nain, 2019).

All of these studies lead to an increase in energy performance, but from a lifecycle aspect of production, it is first necessary to theoretically choose the appropriate machines for each technology.

With this purpose, a point system has been proposed that can be used to evaluate types of mills against the indicators: energy consumption; quantity of material and quantity of gaseous, solid and liquid waste; public needs (Jeswiet, 2016). However, it is not possible to compare different machine sizes of the same type on the basis of energy consumption, quantity of waste and produced products and others.

In the presented problem, it is most expedient to determine the energy per unit of product produced or the so-called relative power consumption at a selected mill type. Therefore, the article examines the problem of choosing the size of drum mills in the design of processing factories versus the lower energy consumption factor. The necessity of the study arises because many scientists study the energy consumption of already installed and operating mills according to the properties of the material to be milled - hardness, size, content and etc. The literature emphasises only the reasons for choosing a type of mill in the design and construction of a technological line by a classical or point method. The choice of type of mill according to size must be guided by the cost of building and maintaining the machinery, the leading criterion being the energy consumption of each machine per tonne of processed ore. Such a condition is fully consistent with sustainable development criteria because lowering energy consumption will lead to improvements in some of the energy efficiency criteria.

Structure of the object to be analysed

When designing a technological line in the mining and processing industry according to the technological requirements, a certain type of mill is chosen. Classification of mills can be done according to different criteria:

- depending on the drum design, they are cylindrical or cylindrical conical;
- according to the discharge, with central discharge or pouring; discharging through a grate; outlet through a peripheral grate;
- according to the type of grinding media they are ball, bar, gravel, autogenous and semi-autogenous;
- according to the number of cameras they are single-chamber or multi-chamber (Minin, 2012).

In processing factories one chamber drum mills are used as milling equipment. For the study, MTP machines (ball mill with grating) are chosen. This model has a low pulp level which results in increased efficiency due to increased impact of the grinding media. They are also known as grate discharging. This is achieved by placing a grid in the semi-receptive chamber between the grating and the bottom of the drum. When the mill is rotated, the milled product passes through it, rises out of the elevator and they outflow from the discharge port. The particles that have reached the required particle size pass through the holes of the grate and enter the semi-receiving chamber from where they are unloaded.

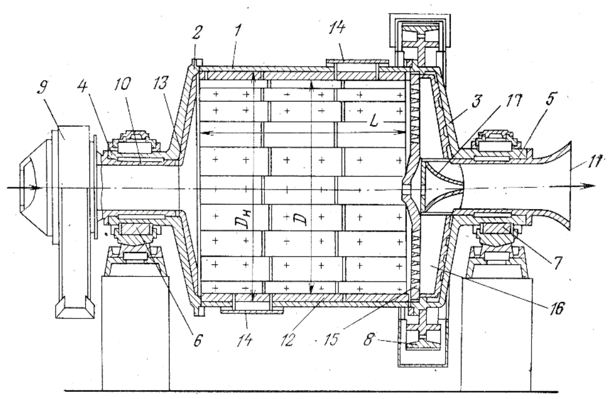

Fig. 1. Drum ball mill with grate

1 - drum; 2 - bottom; 3 - discharge chamber; 4,5-discharge trunnions; 6.7 – bearing seats; 8 - tooth gearing; 9 - combined feeder device; 10,11 - supply and discharge bushings; 12 - drum linings; 13 - lining of the bottoms; 14 - hatch; 15 - discharging grate; 16 - elevator; 17 - unloaded cone; 18-pinion; 19 – shaft

The drum selected for analysis is visualised in Figure 1. It consists of a drum (1) and side bottoms (2). The rotation of the mill is accomplished by means of bearings (6, 7) which are attached to the grippers on the lateral bottoms. On rotation, the material fed in the drum is lifted by the lifter bars of the lining (12), then dropped and milled by impact, grinding and crushing under the action of the grinding media. The milled material is continuously discharged from the discharge port (3), and ore grindings are fed through the feeder port (9) in accordance with a certain technologically chosen filling factor. The performance of the mill, of course, depends directly on the volume of the drum.

The relative power consumption analysis against an appropriate type size is based on the following metrics: engine power, output, energy consumption and cost. For engineering evaluation, the following type sizes were selected for comparison: MTP 4.5x6, MTP 4.5x5, MTP 4x5, MTP3.6x5 and MTP 3.6x4.

Method for determining the productivity of a drum ball mill

For comparison of the defined criteria, the productivity of the selected by size mills must be calculated. In some studies, the energy consumption is determined according to the electricity paid per unit of product (A. Pachanawan, 2017, GH Voicu, 2013), but in this case it is more correct to use a classical methodology for calculating engine power. This is the method used by engineers to determine the basic technological parameters and forces, which includes the steps described below in the text (I. Minin, 2012, Minin et al., 2010).

The light drum diameter is determined using the formula:

$$D_1 = D_\delta - 2\delta, mm \qquad (1)$$

where:

- D_δ – is the drum diameter;
- δ - the thickness of the lining, being between 0.15 ÷ 0.17 mm for the different sizes of mills.

The critical angular speed of the drum is calculated as follows:

$$\omega_{cr} = \sqrt{\frac{2g}{D_1}}, \text{ rad/s}, \qquad (2)$$

where D_1 is the light drum diameter.

The actual angular velocity of the drum is given according to the expression:

$$\omega = \frac{\pi n}{30}, \frac{rad}{s}, \qquad (3)$$

where n is the rotation speed of the drum.

The relative angular speed of the rotation of the drum Ψ is determined by the ratio of the drum speed to the actual angular velocity and the critical angular velocity.

$$\Psi = \frac{\omega}{\omega_{cr}}.100\% \,. \qquad (4)$$

The working volume of the drum for each mill is determined according to the expression:

$$V_1 = \pi R_1^2.L, m^3, \qquad (5)$$

where:

$R_1 = \frac{D_\delta - 2\delta}{2}, m$ - is the drum radius without the lining;

L - drum length.

The mass of the balls is determined according to:

$$M_T = \rho_T V_1 \varphi, \qquad (6)$$

where:

- ρ_T – is the density of the balls;
- φ - fill factor with grinding bodies, which is selected in this case 0,4.

To determine the mass of the balls, their density should be chosen. By known methods the density of the balls is selected according to their diameter, but from a theoretical study it has been found that the balls are of different wear and do not stand symmetrically in the mill drum. It is estimated that the density of the balls is about 4514kg/m^3 and this density does not depend on their diameter (Minin et al., 2014).

The weight of grinding media in the mill is determined according to the dependence:

$$C_T = g.M_T \qquad (7)$$

where g is the Earth's acceleration.

Table 1. *Specification table of the selected type mills*

Parameters	MTP-3600x4000	MTP-3600x5000	MTP-4000x5000	MTP-4500x5000	MTP-4500x6000
the thickness of the lining,mm	110	110	110	120	120
the light drum diameter,mm	3600	360	4000	4500	4500
drum length,mm	4000	5000	5000	5000	6000
the working volume of the drum,m^3	36	45	55	71	85
the rotation speed of the drum, min^{-1}	18,1	18,1	17,4	16,5	16,5
% of the critical angular speed	78,7	78,7	79,9	80,4	80,4
the mass of balls,t	74	93	115	148	177
the weight of grinding media in mill,t	216	238	333	395	-
the weight of the drum,Mmill,t	160	165	265	300	320
power of engine,kW	1000	1250	2000	2500	2500

The weight of the drum is:

$$C_б = g.M_б, N \qquad (8)$$

where $M_б$ – the mass of the drum, the value being taken from the enclosed grinder specification table, Table 1.

The idle power is determined with the equation:

$$N_{idle} = 0{,}5\mu C_6 \omega d \quad (9)$$

where:

- μ – the coefficient of friction in the bearings;
- *d* – the diameter of the collar of the mill bearings.

The extra power depends on the weight of the milling media and is calculated with the expression:

$$N_{add} = 0{,}5.\mu.C_T.\omega.d, W, \quad (10)$$

where μ is the coefficient of friction in the bearings and its value is 0.008.

The next step is determining the power to raise the balls in the drum:

$$N_G = \rho_T.g.L.\omega_{cr}.\Psi^3.R_1^3\left[(1-k_2^4) - \frac{2}{3}\Psi^4(1-k_2^6)\right], W \quad (11)$$

where: k_2 – is the relative radius for the innermost layer of the balls, which is taken according to the values in the tables referenced in the literature. The value is 0.606.

The power to transmit the kinetic energy of the balls is:

$$N_e = 0{,}125\rho_T L.\omega_{cr}^3 R_1^4(1-k_2^4), W \quad (12)$$

Calculated power values are used to calculate the engine power required to drive the mill. In these mills, synchronous motors are used for propulsion and for each type of dimension it is required that drive power is to be calculated according to the formula:

$$N_{engine} = \frac{N_{idle}+N_{add}+N_G+N_e}{1000\eta_\mu}, W \quad (13)$$

where η_μ is the mechanical coefficient of efficiency of the drive.

The total productivity of the drum mill versus the starting product is determined according to the dependence:

$$Q = qV_1, kg/h \quad (14)$$

where q is the specific productivity of the mill.

The specific performance of the mill is determined by the factors on which it depends: grinding mode, type of grinding medium, size of the output and final product, physico-mechanical properties of the grinding material, mill diameter, grinding medium, relative angular velocity of the mill and others. Their impact is accounted for by correction factors, the values of which are established by the practice. They are:

Correction coefficient for the influence of the size of the outcoming ore:

$$K_d = \sqrt[4]{\frac{dh}{25}} = 0{,}83, \quad (15)$$

where dh is the maximum size of the outcoming ore, mm.

Correction factor for the influence of the diameter of the drum:

$$K_D = \sqrt{\frac{3}{D_6}}, \quad (16)$$

where 3 - drum diameter of a reference mill, m.

Correction coefficient for the influence of the relative velocity:

$$K_\Psi = \frac{75}{\Psi} \ , \quad (17)$$

Correction coefficient for the effect of the amount of the milling media:

$$K_\varphi = \frac{75}{\varphi} \quad (18)$$

Correction coefficient for the influence of the size of the milled product:

$$K_\beta = 3.4d_k, \quad (19)$$

where d_k - nominal diameter of the finished product.

Coefficient considering the type of mill chosen $K_{mill} = 1$ if the mill has a grate (in this case) or $K_{mill} = 0.87 \div 0.8$, if the mill is centrally unloaded.

Coefficient for calculating the influence of the digestibility of the ore on the mill performance. This factor is counted from graphic and accepted $K_T = 0.85$.

After determining all the coefficients, the specific productivity of each mill by source product can be calculated according to the dependence:

$$q = \frac{q_0 K_T K_\beta K_{mill}}{K_d K_D K_\Psi K_\varphi}.\frac{\rho_H}{16000}, kg/m^3 \quad (20)$$

where:

- q_0 - reference specific productivity (assumed $q_0 = 2200\, kg/m^3h$);
- ρ_H – a coefficient of bulk density of the ore;
- 1600 – reference bulk density.

Results

Based on the methodology, the productivity (Q/ t) of different types of mills was calculated. The results obtained are shown in Figure 2. It can be seen that reducing the size of the drum also reduces the performance.

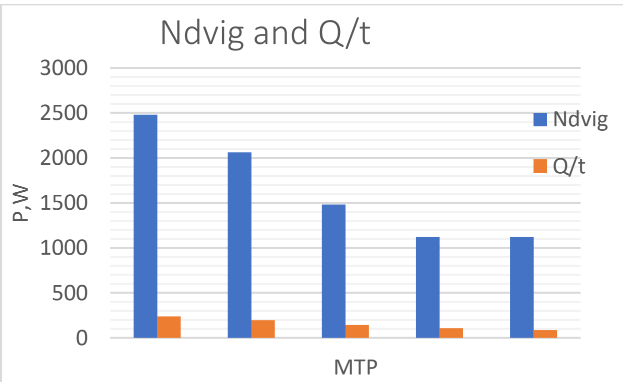

Fig. 2. Productivity and power of engine of the surveyed MTP

Comparison of different types of mills based on relative power consumption

The concept of relative power consumption is introduced because the consumed electricity does not provide an objective estimate of the costs of the processed ore. The relative power consumption $\mathrm{E}, kWh/t$ is the ratio of the calculated power of the mill engine to the productivity of the mill per finished product per unit of time. Changing this value depends on the load of the engine with different loads. Energy efficiency can therefore be used to determine effective operation regimes when changing qualitative characteristics of the incoming ore. The relative power consumption is obtained using the formula:

$$\mathrm{E} = \frac{N_{engine}}{Q}, kWh/t \quad (21)$$

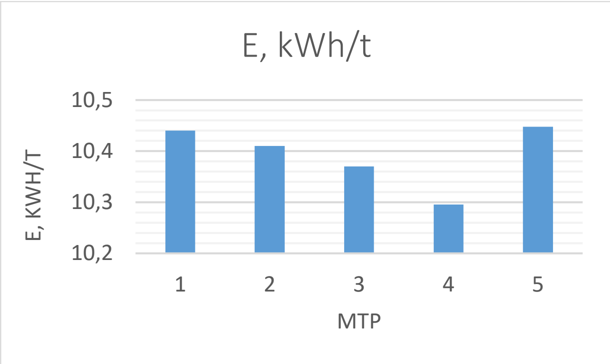

Fig. 3. Relative power consumption of Types MTP

It can be seen that the relative power consumption depends on the size of the mills. In a given order, the energy consumption decreases when the volume decreases, but with excessive volume decrease it increases. The reason is that the mass of the parts of the smaller machines is close to that of the larger machines, resulting in increased idling energy consumption and hence increased energy consumption of small mills. This is visualised in Figure 4, and to achieve the symmetry of the graphs the data on the weight of the mill are divided into 10000.

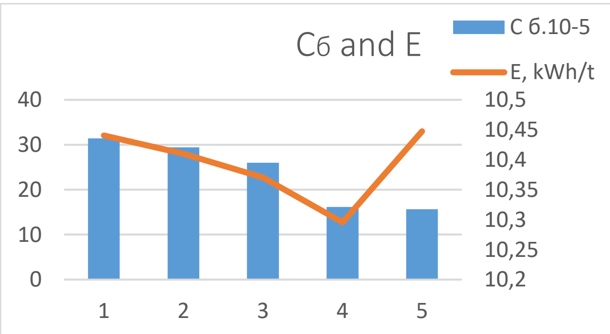

Fig. 4. Drum weight and relative power consumption of types MTP

When deciding on the choice of a type-sized mill aiming to rationalise the electricity consumption, the result obtained should be taken into account. The price factor is not insignificant and can also be included. The price is determined according to the dependence:

$$P = prM_{mill}, euro \quad (22)$$

where pr – the price per unit weight, given conditionally 6 euro per kilogram

– M_{mill} – the mass of the mill.

It can be seen that the reduction of the mill's mass decreases the price, respectively the repair costs, as well as the quantity of the produced product. However, Figure 5 shows that energy consumption increases as the volume of the mill drum decreases, while the productivity is almost unchanged, and this is the key factor in deciding on the size of mills.

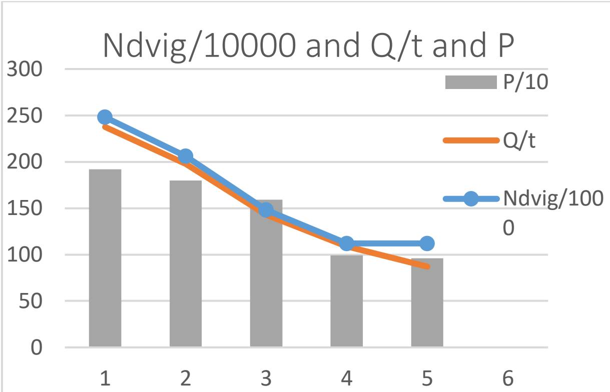

Fig. 5 Engine power, productivity, cost of MTP

After choosing a type-sized mill and building a processing line, it is necessary to define the operating modes. In determining their economic efficiency, it is necessary to analyse the technological mode of the processing plant, according to the boundary conditions of the equipment and the characteristics of the material to be milled, such as grain size, changing the trajectory of the particles (Stoyanov, 2015), the humidity, the hardness, etc. (Assawamartbunlue, 2018). This is related to determining the impact of each of these factors on the energy consumption by measuring and subsequently processing and analysing the data.

Conclusion

It is important that the mills are selected according to their relative power consumption, because in this way it is possible to save not only energy, but also costs for parts, repair, and maintenance. Worldwide, there is an emphasis on choosing a larger machine rather than a few smaller ones, such as rice flour mills. The theoretical study proves this trend.

However, the choice of the type of mill and its size should not only be the relative power consumption of the grinding process, but that of the whole technological line. To achieve a synergic effect from all the phases of processing the ore, it is necessary to analyse the change in energy consumption when changing the production technology. For example, the use of an additional reagent to the mill in order to increase the efficiency of the next flotation process (Boteva, 2002). This action will not lead to a reduction in the mill's relative power consumption, but only to the flotation process. Finally, this will generally improve the energy performance of the whole life cycle due to the increased amount of the extracted metal. This is a future topic of research.

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