DETERMINING THE RELATIVE ENERGY CONSUMPTON OF A JAW CRUSHER DEPENDING ON THE WIDTH OF THE DISCHARGE PORT AND ON THE PARTICLE SIZE DISTRIBUTION OF THE CRUSHING PRODUCT

Teodora Hristova[1], Ivan Minin[2], Dimitar Mitev[3],

[1] University of Mining and Geology "St. Ivan Rilski", 1700 Sofia, teodora@mgu.bg
[2] University of Mining and Geology "St. Ivan Rilski", 1700 Sofia, minin@abv.bg
[3] University of Mining and Geology "St. Ivan Rilski", 1700 Sofia, dimitar_i_radi@abv.bg

ABSTRACT. The article discusses the topic of the specific energy consumption of a complex pendulum jaw crusher. It is driven by an induction motor with a squirrel-cage rotor. The purpose of the study is to determine the effect of two basic parameters on the relative energy consumption of the crusher: the width of the discharge port and the particle size distribution of the product to be crushed. In order to determine the energy performance, some basic parameters have been measured, such as the average diameter of the fragments fed into the crusher, the width of the crusher discharge port, the weight of the crushed material, the average power of the engine phase, the crushing time of the sample, etc. In accordance with the selected target function, energy consumption patterns have been synthesized depending on the width of the discharge port and the particle size distribution of the crushing product. The models obtained have been evaluated using statistical criteria to determine their adequacy in relation to the selected target function. Data processing has been performed through the STATGRAPHICS computer program. It has been found that the relative energy consumption is affected by the two control parameters - the size of the incoming pieces and the width of the crusher discharge port. Relevant conclusions have been made.

Keywords: jaw crusher, asynchronous engine, energy consumption, particle size distribution, discharge port

ОПРЕДЕЛЯНЕ НА ОТНОСИТЕЛЕН ЕНЕРГОРАЗХОД НА ЧЕЛЮСТНА ТРОШАЧКА В ЗАВИСИМОСТ ОТ ШИРОЧИНАТА НА ИЗПУСКАТЕЛНИЯ И ОТВОР И ЗЪРНОМЕТРИЧНИЯ СЪСТАВ НА ПРОДУКТА ЗА ТРОШЕНЕ

Теодора Христова[1], Иван Минин[2], Димитър Митев[3],
[1] Минно-геоложки университет "Св. Иван Рилски", 1700 София, teodora@mgu.bg
[2] Минно-геоложки университет "Св. Иван Рилски", 1700 София, minin@abv.bg
[3] Минно-геоложки университет "Св. Иван Рилски", 1700 София, dimitar_i_radi@abv.bg

РЕЗЮМЕ. В статията е изследван специфичният разход на електроенергия на челюстна трошачка със сложно люлеене на подвижната челюст. Тя е задвижвана от асинхронен двигател с накъсо съединен ротор. Цел на изследването е да се определи влиянието на два основни параметъра – широчина на изпускателния отвор и зърнометричен състав на продукта за разтрошаване върху относителния енергоразход на трошачката. За определяне на енергоразхода са измерени основни параметри като среден диаметър на постъпващите в трошачката късове, широчина на изпускателния отвор на трошачката, тегло на разтрошаваното количество материал, средна мощност на едната фаза на двигателя, време за разтрошаване на пробата и др. Според избраната целева функция са синтезирани модели на енергоразхода в зависимост от широчината на изпускателния отвор и зърнометричния състав на продукта за трошене. Получените модели са оценени посредством статистически критерии за определяне на адекватността им към избраната целева функция. Обработката на данните е извършен чрез компютърна програмата STATGRAPHICS. Установено е, че относителният енергоразход се влияе от двата управляващи параметъра - едрината на постъпващите късове и широчината на изпускателния отвор на трошачката и са направени съответните изводи.

Ключови думи: трошачка, асинхронен двигател, енергоразход, зърнометричен състав, изпускателен отвор

Introduction

Increased demand for production, reduced machine downtime, increased productivity, and the lowering of costs are of all of major importance to the mining industry. To maintain these priorities, the crushing process can be managed in accordance with various goals: minimum costs, high productivity, product quality, high efficiency, energy efficiency, and many more. The task is complicated due to the multitude of factors of the object. In such a case, it is appropriate to select a target that can be estimated from the point of view of real measured values which affect the production process.

Determining the target function and the control factors

The choice of machine mode of operation is made according to various criteria. In this case, a complex pendulum jaw crusher is considered. It is necessary to choose an operating mode for a laboratory jaw crusher in accordance with a specified criterion. To automate the process, the crusher must be considered as a control object. In terms of technological mode, the jaw crusher is classified as an uneven load mechanism. The performance of such mechanisms depends on a number of random factors such as: the particle size distribution, the physical properties of the ore, the mutual arrangement of the individual ore fragments in the feed opening of the crusher, the wear of the lining of the moving and fixed jaws (Irinkov, 1971).

Typically, the objective of automatic control is the stabilisation of: the productivity, the active power of the electric drive or the ore level in the feed opening of the crusher (Radulov et al., 2009). Classical theory recommends that the crusher be automated for maximum productivity (Irinkov, 1971).

The output parameters of the crushing process are:
- the productivity of the jaw crusher in terms of crushed product - q;
- the active power of the crusher's electric drive - P;
- the particle size distribution of the crushed product C_{x2}.

The managed parameters are the ore level in the feed opening and the active power. They are changed through the control parameters: the change of the quantity of feed ore Q, g, the width of the discharge opening - b, mm, and the jaw movement frequency n, s^{-1} (Radulov et al., 2009).

Consequently, the control criteria can be defined according to the power, according to the ore level in the feed opening, as well as according to the particle size distribution. Since a laboratory crusher with a small feed opening is considered, the second criterion hasn't been accepted. The appropriate criteria are the pproductivity and the low energy consumption.

As a criterion, productivity is obtained after measuring the crushing time of a certain quantity of weighed material. Based on performance, the energy consumption $E, kWh/t$ can be calculated as the ratio of the measured crush engine power to the crusher productivity per finished product per unit of time. In this case, for the object under examination, the energy consumption is considered to be the appropriate target function. The energy consumption E is calculated using the formula:

$$\mathrm{E} = \frac{P}{Q.t}, \text{ kWh/t} \quad (1)$$

where:
- E is the power consumed by the crusher's engine;
- Q is the productivity of the crushed product.

For the laboratory crusher tested, there are no energy consumption characteristics specified in relation to the change in the particle size distribution and to the variation in the width of the discharge port. This is the object of the present study.

Experiment Description

The choice of factors in accordance with which the specific energy consumption will be determined is subject to the following requirements:
• each factor must have a certain limit of change i.e. be controllable;
• each factor must be manageable, i.e. to determine the levels in the definition area;
• the parameters of each factor must be measured with accuracy;
• the parameters must be independent i.e. not to be functionally linked;
• the parameters must be compatible so that the joint relationships could be defined.

The following possible parameters have been identified as the managing factors in the study:

1. $\mathrm{D, mm}$ - Average diameter of the fragments entering the crusher. This size is average for the respective fraction class of the selected and pre-sieved material. The experiments were performed with materials of the sizes shown in Table 1. They are consistent with the width of the feed opening of the laboratory crusher.

Table 1
The average diameter of the Fraction class

Fraction class	D	Fraction class	D
+45-55	50	+35-45	40
Fraction class	D	Fraction class	D
+25-35	30	+15-25	20

2. $\mathrm{b, mm}$ - Width of the discharge port of the crusher. This parameter has also been selected in accordance with the dimensions and capabilities of the laboratory machine. The width of the discharge port has the following values: 6, 8, 12, 16, and 20 mm.

The relative energy consumption as a target function is obtained as the ratio of the average crusher engine power measured by means of the measuring and recording device to the performance per unit of time - $\mathrm{E, Ws/g}$. The three-phase digital multi-function AC powermeter of SATEC PM130EH is used as a measuring instrument.

A parameter such as the angular rotation speed of the eccentric shaft cannot be changed, so it does not participate as a control factor.

Due to the uniqueness requirement, the interconnected factors are eliminated, e.g. the crusher's degree of crushing which is related to the average diameter of the fragments entering the crusher and the width of the discharge port (Ackermann et al., 1982).

When determining the energy consumption, the disturbing effects that affect the performance and the size of the crushed product are as follows: the particle size distribution of the ore; the ore hardness; the uneven material feed. To neutralise the influence of the above disturbing factors, material of the same hardness was examined and parameter measurements were made under the conditions of continuous feed of material.

The following parameters were measured during the experiment:

- D, mm the average diameter of the pieces entering the crusher;
- b, mm - the discharge port width of the crusher;
- M_{CYM}, g - the weight of the crushed material;
- P_1, W - the average power of one phase of the engine;
--t, s - the time taken to crush the sample.

Results

To determine the energy consumption, a mathematical model needs to be created that will take into account the real statistical properties of the dependencies in the object. Since there is a change in a number of factors, such as the power, the engine load, and the different shape of the crushed product, it is appropriate to make a non-deterministic rather than a statistical model (Bozhanov, 1971). The first step of the modeling is converting the results obtained through the experimental measurements with a laboratory crusher into a Fischer matrix. The matrix is visualised in Table 2.

Table 2
Fischer matrix

	X_1	X_2	Y_2
№	**D, mm**	**b, mm**	**E,Ws/g**
1	50	20	0.006
2	50	16	0.009
3	50	12	0.011
4	50	8	0.01
5	50	6	0.020
6	40	20	0.006
7	40	16	0.008
8	40	12	0.010
9	40	8	0.014
10	40	6	0.015
11	30	20	0.006
12	30	16	0.007
13	30	12	0.008
14	30	8	0.014
15	30	6	0.016
16	30	20	0.006
17	20	16	0.006
18	20	12	0.006
19	20	8	0.014
20	20	6	0.014
21	20	6	0.016

The processing of the data from Table 2 is performed through a statistical analysis (Bozhanov, 1979; Nalimov, 1965) by the STATGRAPHICS program which is suitable for scientific research. Energy consumption patterns have been synthesised by means of the program, and various criteria have been calculated for determining the reliability and adequacy of the model. Among those are the Student's t-criterion, the P-criterion, the F-criterion, the multiple correlation criterion, the corrected multi-correlation coefficient, and the mean absolute error.

Using these statistical means, an interval known as the confidence interval is defined in which the highly probable true value of the parameter evaluated is determined. The P-criterion gives us the confidence probability and it must be less than 0.05.

In addition to the confidence interval, the significance of each factor is checked. The significance of the coefficients is determined according to the Student's t-criterion for certain degrees of freedom, which, in this case, must be more than 8.

The F-criterion shows the influence of the controllable (managed) factors on the output parameter. Its value is aimed to be high, i.e. the energy consumption is manageable.

The Multiple Correlation Criterion and the Multiple Correlation Factor provide information on the extent of the relationship between the output parameter and the functions included in the model, as well as on the adequacy of the resulting model.

Various models have been obtained from the statistical surveys, most of which have a low multiple correlation factor R^2 (for example, 85.38% for the M3 model, or 41.5% for the M7 model) and an adjusted multiple correlation factor $R^2_{(adj)}$(for example, 83.75% for M3 or 38.45% for M7).

The value of the confidence probability indicator (P-criterion = 0 or P = 0.0016) for the cited models is below the critical, i.e. these models are assumed as inadequate. The basic values of the parameters of all models are given in Table 3. Based on the values in the table, it can be determined that the M6 model has the best parameter and it is the only adequate one for the selected control function of energy consumption.

Table 3
Values of model parameters

model	R^2, %	$R^2_{(adj)}$, %	P-criterion	F-criterion
M 1	85.64	84.04	0.0302	46.96
M 2	82.86	81.96	0.0807	45.96
M 3	41.5	38.45	0.0016	13.48
M 4	47,66	47,66	0.0004	18,22
M 5	68.91	67.28	0.0027	42.13
M 6	92.92	92.92	0.0000	262.46
M 7	85.38	83.75	0.0000	52.56
M 8	93.01	92.85	0.6081	126.59
M 9	88.66	87.40	0.0029	70.42
M 10	93.72	93.39	0.1344	141.93

Table 4
M6 model parameters

Parameters	Value	Standard error	T-statistics of Student		P criterion
$\frac{D}{b}$	0.00283042	$1.747*10^{-4}$	16.2005		0.0000
	Amount of squares of the model	*Degrees of freedom*	*Average on squares of the model*	*F criterion*	Significance of F
Model	$2.554*10^{-3}$	1	0.00255424	262.46	0.0000
residue	$1.946*10^{-4}$	20	9.73210^{-6}		
Total	0.00274888	21			
Multiple correlation coefficient				92.9193%	
Corrected Multiple Correlation Factor				92.9193%	
Standard error				0.00311962	
Average Absolute Error				0.00230522	
Stats Darban- Otsan				0.654328	

Among the examined models, M 7 and M 8 have excellent parameters of the correlation coefficients, but in model M 8 the value of the confidence probability index (P-criterion = 0.6081) for the model is above the critical, i.e. it can be assumed that the model is inadequate for the selected target function.

Analysing the parameters of this model, it can be seen that the multi-correlation coefficient R^2 is 92.92% and the adjusted multi-correlation coefficient $R^2_{(adj)}$ is over 92.92%. The value of the confidence probability index (P-criterion = 0.0000) for the model is below the critical one, i.e. it can be assumed that the model is adequate.

Of all obtained models, the best-performing is the M 6 model (Table 4) and it can be considered as a model of great adequacy. This model has the best performance indicators among all others.

Then we choose the equation of the model with natural variables to be as follows:

$$E = 2{,}8310^{-3}\frac{D}{b}, KWh/t \quad (2)$$

Table 5 shows the basic parameters along with the obtained values for each examined model.

Table 5
Basic parameters of model study

MODEL №	*D*	*b*	*D.b*	*constant*	$\frac{D}{b}$
1.	*8.2937*$*10^{-5}$	*-7.69796*$*10^{-4}$	-	*0.0170376*	-
2.	*-3.8988*$*10^{-4}$	*-3.39282*$*10^{-4}$	-	-	-
3.	-	-	*1.1457*$*10^{-5}$	*0.0155199*	-
4.	-	-	*1,6125*$*10^{-5}$	-	-
5.	-	-	-	*0.00399301*	*-1.1457*$*10^{-5}$
6.	-	-	-	-	*2.83042*$*10^{-3}$
7.	*-7.69796*$*10^{-4}$	-	-	*0.00847669*	*1.84803*$*10^{-4}$
8.	*2.437*$*10^{-4}$	-	-	-	*2.622*$*10^{-3}$
9.	-	*-5.193*$*10^{-4}$	-	*3.413*$*10^{-3}$	*8.959*$*10^{-4}$
10.	-	*1.063*$*10^{-4}$	-	-	*2.587*$*10^{-3}$

Conclusions

The results obtained from the measurements and the statistical analysis of the relative energy consumption of the crusher show the following:

- the relative energy consumption is influenced to a large extent by two parameters, namely the size of the incoming pieces and the width of the discharge port of the crusher;
- when increasing the size of the input fragments, the relative energy consumption of the machine is increased, which is most probably due to the fact that the larger of size of the material increases the degree of crushing, which in turn increases the power required for the material to be crushed;
- increasing the width of the discharge port of the crusher reduces the relative energy consumption which is due to the fact that a larger-sized material at the discharge port of the machine means a low rate of crushing and a higher productivity that is the denominator of the energy consumption.

The aim of a future study of the team is to determine the effect of the swing frequency of the pendulum jaw on the energy consumption. For this purpose, an induction motor needs to be driven by an inverter. When adjusting the swing frequency of the jaw by means of a frequency inverter, it distorts the sine curve of the supply current. This state is described as the "presence of harmonics". Thus, in productivity management by means of the motion frequency of the jaw, it is likely to have harmonic constituents in excess of the standard allowances.

References

Акерман, Ю., Г. Букаты, В. Олевский и др. Справочник по обогащению руд, М., Недра, 1982. (Ackerman, Yu, G. Bukaty, V. Olevskyi et al., Spravochnik po obogashteniyu rud, Moskva, Nedra, 1982.)

Божанов, Емил С., Иван Н. Вучков. Статистически решения в производството и научните изследвания, С., Техника, 1979. (Bozhanov, Emil S., Ivan N. Vuchkov. Statisticheski reshenia v proizvodstvoto i nauchnite izsledvania, Sofia, Technika, 1979.)

Иринков, Ст. Автоматизация на процесите в мините и обогатителните фабрики, ДИ Техника, 1971. (Irinkov, S. Avtomatizatsia na protsesite v minite i obogatitelnite fabriki, DI Technika, 1971.)

Налимов, В. В., И. А. Чернова, Статистические методы планирования экспериментов, М., Наука, 1965. (Nalimov, V. V., I. A. Chernova. Statisticheskie metodai planirovaniya eksperimentov, Moskva, Nauka, 1965.)

Радулов, Г., Д. Парашкевова. Автоматизация на производството в минните предприятия, МГУМ, С., 2009. (Radulov, G., D. Parashkevova. Avtomatizatsia na proizvodstvoto na minnite predpriatia, MGUM, Sofia, 2009.)