Annals of the University of Petrosani, Electrical Engineering, 20 (2018)

DETERMINATION OF THE INFLUENCE OF JAW MOVEMENT FREQUENCY OF JAW CRUSHER ON ENERGY CONSUMPTION

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Abstract: In the paper, in accordance to the theory, it is shown that the relative energy consumption of a jaw crusher depends on the average diameter of the material entering the crusher and the width of the discharge port. An experimental study has shown that the energy consumption depends also on the frequency of the jaw swing. In the study a jaw crusher with a complex swing of a moving jaw is used and it is driven by an asynchronous motor with a squirrel-cage rotor. The rotational speed of the asynchronous motor is controlled by an inverter, and this frequency determines the swing frequency of the jaw. A statistical model developed in the middle of the STATGRAPHICS program demonstrates the influence of the rotation speed of the engine driving the crusher.

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

1. INTRODUCTION

The new standard EN 50160 replaces the previous one from 1980 - BDS 10 694-80, which introduces stricter criteria for energy quality indicators. The aim is to reduce electricity consumption and to increase its quality compared to the previous one, which is active in Bulgaria. Also, in accordance to the 1972 Rome Club Agreement, it is necessary to abide by the criteria for sustainable development in all sectors. In the mining industry, one of the most energy intensive objects is the crusher. For the implementation of the legal norms it is necessary to determine the factors that affect energy consumption. To determine the factors affecting the energy consumption of the crusher, it is necessary

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first to clarify the mechanism of crushing the ore and the method of determining the productivity.

2. THEORETICAL DETERMINATION OF THE OPTIMAL ANGULAR VELOCITY OF THE ECCENTRIC SHAFT OF JAW CRUSHERS

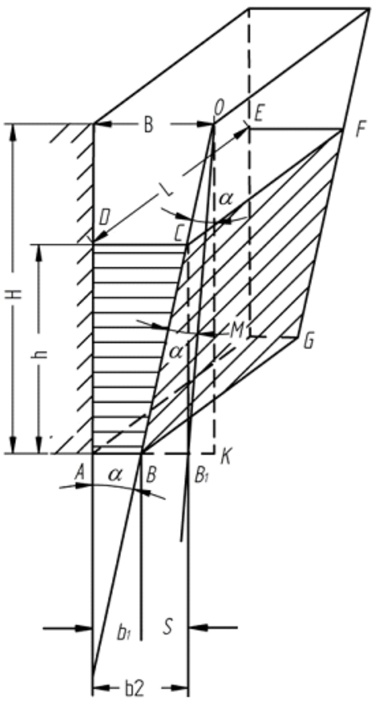

Fig. 1. Unloading the produced stuff from a jaw crusher at an optimum eccentric shaft rotation speed

Fig. 1 shows a drawing of a jaw crusher with an eccentric shaft. When the moving jaw is removed from the static [4], the crushed product is freely discharged through the disharge port of the crusher under its own weight. With each move of the jaw, only ore pieces located below the level of the CD surface can fall. At this level, the width of the crushing chamber at the time of completion of the working stroke is equal to the width of the crushing disharge port of the crusher at maximum movement of the swinging jaw. The disharged material is located in the ABCDEFGM prism volume. The size of the ore fragments present in the volume of this prism may be larger or smaller than the minimum width of the discharge port. If the size of ore fragments is larger, it can be assumed that this is as a result of the limited time of unloading the crushed material constituting half a turn of the eccentric shaft.

The time for one move of the jaw must be sufficient to pass the crushed ore fragments under their own weight to the horizontal level *CDEF* located at a height *h*. The time for one swing of the jaw is equal to the half stroke of the eccentric shaft. It is given by the mathematical equation:

$$\boldsymbol{t = \frac{1}{2}\frac{60}{n} = \frac{30}{n}, s} \qquad (1)$$

where *n* is the eccentric shaft rotation speed, $\boldsymbol{min^{-1}}$. In accordance to the law of the free fall of bodies, the path *h* is determined by the dependency: $\boldsymbol{h = \frac{1}{2}gt^2}$ from which it follows that

$$\boldsymbol{t = \sqrt{\frac{2h}{g}}}, \qquad (2)$$

where *g* is the acceleration of the earth, *m/s*^{2}.

Equalizing the equal parts of (1) and (2) for *n* the result is:

$$\boldsymbol{n = 30\sqrt{\frac{g}{2h}}\, min^{-1}} \tag{3}$$

The height *h* is calculated from the rectangular triangle BB_1C.

$$\boldsymbol{h = \frac{s}{tg\alpha} = \frac{b_2 - b_1}{tg\alpha}, m.} \tag{4}$$

By replacing the right part of (4) in (3) the result for *n* is:

$$\boldsymbol{n = 30\sqrt{\frac{g.tg\alpha}{2(b_2 - b_1)}} = 30\sqrt{\frac{g.tg\alpha}{2s}}, min^{-1}} \tag{5}$$

where: $\boldsymbol{\alpha}$ - is the angle of gripping; $\boldsymbol{b_1}$- the minimum width of the discharging port, *m*; $\boldsymbol{b_2}$- the maximum width of the discharging port, *m*; *s*- swing of the moving jaw, m.

The resulting revolutions are called theoretical. The actual revolutions will be obtained by entering a correction coefficient:

$$\boldsymbol{n_Д = k_1 n, min^{-1}} \tag{6}$$

where: $\mathbf{n, min^{-1}}$ is the theoretical rotation speed of the eccentric shaft; $\mathbf{k_1 = 0,75 \div 0,9}$ - a friction coefficient between the crushed product and the crushing plates.

3. DETERMINING THE PRODUCTIVITY OF THE JAW CRUSHER

The bulk of the crushed product that is unloaded for one turn of the eccentric shaft at optimum rotational speed is equal to the prism volume *ABCDEFGM* (fig.1). Taking into account this volume, the material with reduce size of the crusher is calculated:

$$\boldsymbol{Q_v = 60k_1k_pnV = 60k_1k_pn \frac{(b_2+b_1)(b_2-b_1)}{2tg\alpha}L, m^3/h} \tag{7}$$

where: *L*,*m* is the length of the crusher receiving port; $\boldsymbol{k_1}$ is a coefficient for the crusher type. For crushers with simple swing of the jaw $\boldsymbol{k_1 = 1}$, and for crushers with complex swing $\boldsymbol{k_1 = 1,2}$; $\boldsymbol{k_p}$ - a coefficient of bulk density of the ore. The mass productivity is calculated by considering the density of the ore:

$$\boldsymbol{Q = \rho.Q_v, t/h} \tag{8}$$

where $\boldsymbol{\rho, t/m^3}$ is the density of the crushed product.

4. DETERMINING THE ENGINE POWER OF THE JAW CRUSHER

The load of the engine when operating a jaw crusher depends on many factors, some of which cannot be identified. This explains why no precise theoretical formula has been created until now, that will make be possible to determine the driving power of the crushers. The required power of the Alice-Chalmer crushers, for example, is determined in accordance to the Bond hypothesis using the Bond index [4]. It represents the relative energy absorption of ores and is determined on the basis of experimental results. In accordance to the theory of Bond, the energy consumed for crushing a ton of ore will be:

$$\boldsymbol{W} = \boldsymbol{k}_{\text{CT}}\left(\frac{\mathbf{10}\boldsymbol{w_i}}{\sqrt{\boldsymbol{b}}} - \frac{\mathbf{10}\boldsymbol{w_i}}{\sqrt{\boldsymbol{D}}}\right), \boldsymbol{kWh/t} \tag{9}$$

where: $\boldsymbol{w_i}$ is the Bond index, $\boldsymbol{kWh/t}$; *b* - the dimensions of the square holes of the sieve through which 80% of the finished product passes or the width of the discharge port of the crusher, *m*; *D*- the dimensions of the square holes of the sieve through which 80% of the product entering the crusher or the average diameter of the class fraction entering the crusher port, *m*; $\boldsymbol{k}_{\text{CT}}$ - the crushing stage coefficient. For crushing the big class fractions $\boldsymbol{k}_{\text{CT}} = \mathbf{0,75}$.

Then the equation for crushing power is:

$$\boldsymbol{N}_{\text{ДВ}} = \frac{\boldsymbol{W}.\boldsymbol{Q}}{\mathbf{1000}\boldsymbol{\eta}_{\text{M}}}, \text{kW} \tag{10}$$

where $\boldsymbol{\eta}_{\text{M}} = \mathbf{0,85} \div \mathbf{0,88}$ is the mechanical efficiency of the asynchronous motor of the crusher.

5. DETERMINING THE RELATIVE ENERGY CONSUMPTION OF THE JAW CRUSHER

In accordance to the reviewed theory, the relative energy consumption can be determined by the formula:

$$\boldsymbol{E} = \frac{\boldsymbol{N}_{\text{ДВ}}}{\boldsymbol{Q}} = \frac{\boldsymbol{W}}{\mathbf{1000}\boldsymbol{\eta}_{\text{M}}} = \frac{\boldsymbol{k_{CT}}}{\mathbf{1000}\boldsymbol{\eta}_{\text{M}}}\left(\frac{\mathbf{10}\boldsymbol{w_i}}{\sqrt{\boldsymbol{b}}} - \frac{\mathbf{10}\boldsymbol{w_i}}{\sqrt{\boldsymbol{D}}}\right), \boldsymbol{kWh/t} \tag{11}$$

The conclusion from the above discussed theory is that the energy consumption depends only on the parameters: *D, b* and the type of crushed product but does not depend on the eccentric shaft revolution.

6. EXPERIMENT

6.1. Experiment Planning

The purpose of the experiment is to determine the effect of the speed of the engine on energy consumption. The following input parameters are defined and they will change:

1. The average diameter of the class fraction entering the crusher - $\boldsymbol{D, mm}$. Prior to the experiment, some material with the following 50, 40 and 30 mm class fraction was selected and pre-sieved. They are compliant with the width of the feed port of the crusher [3].
2. The width of the discharge port of the crusher - $\boldsymbol{b, mm}$. The width of the discharge port has the following values: 8 ,12,16 and 19mm. The parameter has also been selected in accordance to the dimensions and capabilities of the laboratory machine.
3. The frequency of rotation of the asynchronous motor f, Hz. The following frequencies were selected: standard - 50 Hz, reduced 40 Hz and 30 Hz. At lower frequencies of 25 Hz it was found out that the feed port of the crusher has been obstructed.

The relative power consumption as a target function is obtained through the ratio of the average crusher engine power measured by the measuring and recording device per unit time - $\boldsymbol{E, Ws/g}$.

Homogeneous material is delivered continuously during the measurement [1]. During the experiment, the values *D, mm*, - *b, mm* and *f, Hz* were changed. The following parameters are measured in the experiment:
- $\boldsymbol{M_{CYM}, g}$ - the weight of the crushed material;
- $\boldsymbol{P_1, W}$ – the average power of one phase of the engine;
-$\boldsymbol{t, s}$- time to crush the sample.

6.2. Description of the experimental pattern

The experiment was made with a laboratory jaw crusher with complex swing of a moving jaw driven by an asynchronous motor with a squirrel-cage rotor with the power of 2.2kW. The frequency of the stator voltage is regulated by the Electroinvent ELDI / B -2.2k / 380V frequency PWM inverter. The three-phase digital multi-function, AC powermeter of SATEC PM130EH is used as a measuring instrument.

6.3. Results

It is necessary to create a mathematical model for determining the function of the energy consumption, which depends on the values of the measured parameters: the inverter frequency, the average diameter of the class fraction entering the crusher and the width of the discharge port of the crusher. This model will take into account the real statistical properties of the dependencies in the object. In this case, it is appropriate to make a non-deterministic, rather than a statistical model [2], because we consider the change in a number of factors such as the engine power and the engine speed, the engine load. The calculation of the data from the experiment was done by statistical analysis [2, 5] through the STATGRAPHICS program. This is a program that finds out the proper target function for minimum energy consumption according to the frequency inverter settings. The program has synthesized energy consumption patterns, and the adequacy of the model is proved by the following criteria: Student's t-criterion, the P -criterion, the

F-criterion, the multiple correlation criterion, the corrected multi-correlation coefficient and the mean absolute error. The actual value of the evaluated parameter is in the so-called trusted interval. The importance of the individual criteria is as follows:

- The P-criterion determines the trusted probability and its value should be less than 0.05;

- Student's t-criterion determines the significance of the coefficients for certain degrees of freedom, which in this case should be more than 8;

- the F-criterion shows the influence of the controllable factors on the output parameter and the aim is that its value be high, i.e. the energy consumption is manageable.

-the $\boldsymbol{R^2}$ и $\boldsymbol{R^2_{(adj)}}$ are the criteria for the multiple correlation and the multiple correlation coefficient. They provide information for the extent of the relationship between the output parameter and the functions included in the model, as well as the adequacy of the resulting model.

Table1. ***Values of model parameters***

model	$\mathbf{R^2}$, %	$\mathbf{R^2_{(adj)}}$, %	P-ratio- b	P-ratio -	P-ratio	F-ratio
M 1	94,743	94,042	b -0,491	D - 0,743	f- 0,001	90,12
M 2	95,583	95,245	D*b–0,1.10^{-3}	Constant - 0	f- 0,025	139,7
M 3	30,872	21,655	D/b - 0,024	Constant-0,015	f- 0,921	3,35
M 4	86,509	85,666	D/b - 0,358	Constant - 0	f -0,1.10^{-3}	51,3
M 5	94,569	94,229	b - 0,1.10^{-3}	Constant - 0	f -0,277	139,31
M 6	89,552	88,899	D/b - 0,067	Constant - 0	sqrt(f) - 0	68,57
M 7	89,307	88,639	D -0,084	Constant - 0	sqrt(f)-0,502	66,82
M 8	94,498	94,154	b – 0, 3.10^{-3}	Constant - 0	sqrt(f)-0,322	137,42
M 9	46,131	42,764	f/b – 0,001	Constant - 0	---	13,70
M 10	61,256	61,256	f/D - 0,1.10^{-3}	Constant - 0	--------	26,88
M11	87,021	87,021	b/f- 0	Constant - 0	--------	113,99
M12	91,233	90,685	b/f - 0,06	Constant - 0	D - 0,0136	83,25
M13	89,494	88,837	D -0,029	Constant - 0	f -0,395	68,15
M14	81,826	81,826	D/f	Constant - 0	--------	76,54

Different models were obtained after examining the dependencies determined by the STATGRAPHICS program. The basic values of the parameters of all models are given in Table 1. Various models have been obtained from the statistical surveys, most of them having good correlation values - $\mathbf{R^2}$ (e.g., 94.743% for M1, or 94.57% for model M5), and the corrected multiple correlation coefficient $\boldsymbol{R^2_{(adj)}}$ (e.g., 94.0425% for M1 or 94.2298% for M5). These coefficients are at the border value of the recommended 95%. The drawback of the models is that the trust P-criterion has high values (P-criterion = 0.77437 for the D parameter in model M1 or P criterion for the f parameter -0.277). These values for the cited models are above the critical one, i.e. it can be assumed that these models are inadequate.

Based on the model data in the table, it can be determined that M2 has the best parameters.

Table 2. ***M2 model parameters***

Parameter	**Estimate**	**Standard Error**	**T statistic of Student**		**P-Value**
constant					
D*b	2,21432E-05	4,33642E-06	5,10633		0,0001
f	0,000152824	6,18155E-05	2,47226		0,025
	Sum of Squares	*Df*	*Mean Square*	*F-Ratio*	P-Value
Model	0,00676644	3	0,00338322	139,7	0
Residual	0,000387475	27	2,42172E-05		
Total	0,0071539	30			
R-squared				95,5837%	
R-squared (adjusted for d.f.)				95,2452%	
Standard Error of Est				0,0049211	
Mean absolute error				0,00396103	
Durbin-Watson statistic				2,33315	

The $\boldsymbol{R^2}$ correlation coefficient of M2 is 95.5837% and the corrected multiple correlation coefficient $\boldsymbol{R^2_{(adj)}}$) is 95.2452% (Table 2). The recommended multiple correlation coefficient is 95% and can therefore be accepted as a proper. The value of the trust probability indicator (P-criterion = 0.0001 and 0.025) for the model is below the critical one and the model can be assumed to be adequate. The model with natural variables to be:

$$\mathbf{E = 0,0000221432 * D * b + 0,000152824 * f \quad, KWh/t} \qquad (12)$$

This is the model for which the frequency inverter should be set at certain parameters of the class fraction of input ore and the width of the discharge port. For the same study, more accurate models with a higher correlation coefficient can be obtained with more experiments (more than 30). In a previous study [3] it has been found out that the function of the energy consumption depending on the size of the input pieces and the width of the discharge port is:

$$\mathbf{E = 2,8310^{-3}\frac{D}{b}, KWh/t} \qquad (13)$$

In the present study, this dependence was not confirmed - M3, M4 and M6. The reason is that in this case there is a complex interaction of three factors. Thus, when adjusting the frequency of the engine speed, the result will be changes of the time for crushing the material and hence its load. Therefore, in the statistical surveys, a connection was sought for between the individual parameters. From the results, it can be concluded that the width of the crusher discharge port is directly proportional to the energy consumption (M8, M9 and M11). Also, the diameter of the pieces entering the crusher - M7, M10, M13 and M14 is also directly proportional to the energy consumption.

7. CONCLUSIONS

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

- the relative power consumption is influenced largely by the three parameters, namely the diameter of the input pieces, the width of the discharge port of the crusher and the rotation speed of the engine;
- the relative energy consumption of the asynchronous motor increases as the diameter of the input pieces increases. The reason is most likely that larger pieces of material increase the degree of crushing, which increases the power needed to crush the material;
- when reducing the width of the discharge port of the crusher, the relative energy consumption due to the increase in the crushing rate is also increased.
- when reducing the swing frequency of the jaw, the crusher decreases the relative energy consumption due to the increase in the crush chamber discharge time and reduces the engine load.

For future research, the team aims at measuring and detecting the presence of harmonics in regulating the engine speed through a frequency inverter. The presence of harmonics leads to a distortion of the sine wave of the supply current. Thus, through control of the energy consumption by means of the frequency swing of the jaw, it is possible to generate harmonic constituents above the allowed ones in the standard. The experiment data will be useful in finding an appropriate target function for the control of the frequency inverter.

Acknowledgements This research was supported by the Ministry of Education and Science through the Project“ Energy Quality Test for Asynchronous Motor Operation, Driving Crusher", contract 155/2018).

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